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A Guide for Pre- and Postfire Modeling and Application in the Western United States

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Abstract

The current study reviews a range of five models commonly used in postfire hydrologic assessments: the Rowe Countryman and Storey (RCS), the U.S. Department of the Interior U.S. Geological Survey (USGS) Linear Regression Equations, the U.S. Department of Agriculture (USDA) Windows Technical Release 55 (TR-55), Wildcat 5, and the U.S. Army Corps of Engineers (USACE) Hydrologic Modeling System (HEC-HMS). The models are applied to eight diverse basins in the western United States (Arizona, California, Colorado, Montana, and Washington) affected by wildfires and assessed with regards to input parameters, calibration methods, model constraints, and performance. No one model is versatile enough for application to all study sites. Results show inconsistency between model predictions for peak discharge events across the sites and less confidence associated with larger return periods (25- and 50-year peak flow events) and with postfire predictions. The RCS method performs well, but its application is limited to southern California. The USGS linear regression model has wider regional application, but performance is less reliable at the large recurrence intervals and postfire predictions are reliant on a subjective modifier. Of the three curve number based models, Wildcat 5 performs best overall without calibration, while the calibrated TR-55 and HEC-HMS models show significant improvement in prefire predictions. Results from our study provide information and guidance to ultimately improve model selection for postfire prediction and encourage uniform parameter acquisition and calibration across the western United States. This study also includes detailed methodology for model set up and execution, application of models to a case study, and brief description of in situ postfire hydrologic monitoring.

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by

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Introduction

Wildfires alter land surfaces, land-atmosphere interactions, and hydrologic responses (Debano 2000; Moody and Martin 2001; Beringer et al. 2003; Ice et al. 2004; Prater and DeLucia 2006; Cydzik and Hogue 2009; Pierson et al. 2008; Jung et al. 2009; Montes-Helu et al. 2009; Burke et al. 2010). Wildfires also are occurring more frequently at the wildland-urban interface and impose threats on development and human populations (Randeloff et al. 2005; Cannon and DeGraff 2009). Climate change and increasing wildfire frequency add to postfire hydrologic variability (Westerling et al. 2006;Trouet et al. 2008; Cannon and DeGraff 2009), and the ability to accurately predict postfire flood potential is vital for both human safety and effective and efficient management of State and regional resources.

The Forest Service, an agency of the U.S. Department of Agriculture (USDA), deploys Burn Area Emergency Response (BAER) teams as soon as conditions permit, to determine values at risk across the forests. BAER teams also are responsible for hydrologic predictions and focus on estimating potential increases in postfire runoff and sediment that place downstream values at risk or threaten human life and natural resources. Hydrologic assessments undertaken by BAER teams vary by region, fire, modeler, accessibility, and ease of use (Foltz et al. 2009), and generally there is a lack of consistency in postfire hydrologic assessments. In addition, performance of many of the applied hydrologic models has not been well documented within the postfire context.

Numerous models and techniques are available to predict postfire peak discharge, varying significantly in complexity and ease of use. The operational BAER teams typically use empirical, event-based models to accommodate rapid assessment. A Forest Service survey on BAER models (Napper 2010) found that 26 percent of modelers use the U.S. Department of the Interior, U.S. Geological Survey (USGS) Linear Regression Model, 10 percent use the USDA Windows Technical Release 55 (TR-55), 23 percent use Curve Number (CN) methods (no specific model platform mentioned), 9 percent use Wildcat 4 or Wildcat 5, 20 percent use the Water Erosion Prediction Project, 2 percent use the Fire Enhanced Runoff and Gully Initiation (FERGI), 8 percent use the Rowe Countryman and Storey (RCS), and 2 percent use the U.S. Army Corps of Engineers (USACE) Hydrologic Modeling System (HEC-HMS) model. The BAER survey brings attention to the wide range of models being utilized by the wildfire community and the need for systematic approaches in their application (i.e., gathering parameters and adjusting models for postfire conditions). In general, the BAER models have been extensively utilized and validated over various watersheds. However, they are rarely evaluated under post-fire conditions, where application of the models often falls outside of the developed range of parameters resulting in unreliable predictions. (Cydzik and Hogue 2009; Chen et al. 2013). Models chosen for review in the current study include the RCS, USGS Linear Regression Equations, TR-55, Wildcat 5, and HEC-HMS. Although other empirical equations or methods have been developed that utilize peak discharge measurements from burned watersheds (Moody 2012; Schaffner and Reed 2005; Reed and Schaffner 2007; Reed et al. 2012), the current assessment focuses on a suite of models routinely used and recommended by our Forest Service collaborators.

The RCS method consists of look-up tables for discharge and erosion rates for southern Californian watersheds based on in situ observations (Rowe et al. 1949). Notable fires, such as the 2003 Old and Grand Prix Fires and

the 2009 Station Fire in California, utilized the RCS method for BAER postfire hydrological predictions and management assessments (Biddinger et al. 2003; Moore et al. 2009). The USGS Linear Regression Equations have been used to estimate peak discharge across the United States, primarily under prefire conditions. The USGS method uses relations between discharge and climatic and physical characteristics of the contributing area and is often applied to ungauged sites where there is no observational data. The regression equations have been developed for each State and recently have been integrated into an interactive geographic information systems framework (U.S. Department of the Interior, U.S. Geological Survey 2013). A modifier also has been developed to utilize the established equations for postfire predictions (Foltz et al. 2009).

The TR-55, Wildcat 5, and HEC-HMS models utilize CN methodology, but vary by model parameters, constraints, and developed interface. Several of the models have been previously applied to notable fires, such as the 2002 Hayman Fire (Wildcat 4; Robichaud et al. 2003) and 2000 Valley-Complex Soil Conservation Service (SCS) CN method; Burned Area Emergency Rehabilitation Team 2000) and the 2003 Old Fire (HEC-HMS; Cydzik and Hogue 2009). The CN method is noted for having more uncertainty in predictions when estimating at the extremes, especially during low flow and low rainfall conditions (Hawkins 1975). Cydzik and Hogue (2009) analyzed the HEC-HMS under both pre- and postfire conditions. Results showed significant changes from pre- to postfire parameter values as well as trends in several variables (initial abstractions, curve number, and lag time) over a 3-year recovery period. The CN returned to prefire values by the end of the second postfire year, initial abstractions reached prefire conditions after the third rainy season, and the lag time remained lower than prefire values throughout the 3-year study period (Cydzik and Hogue 2009; Chen et al. 2013).

The current study undertakes one of the first model intercomparison studies for a range of event-based hydrologic models utilized under both pre- and postfire watershed conditions. We outline the various modeling platforms, parameter acquisition (inputs and outputs), and necessary parameter alterations for pre- and postfire simulations. Specifically, the objectives of our work are to: (1) review a range of event-based hydrologic models utilized in postfire modeling of peak flow events, (2) evaluate the models' performance across a range of diverse fire sites, including Arizona, southern and northern California, Colorado, Montana, and Washington, (3) demonstrate potential improvements in calibrated models where data are available, and (4) provide guidance on model constraints and application in diverse postfire regimes. Ultimately, we hope to facilitate a uniform framework and calibration approach for improved postfire hydrologic practices and modeling assessments across multijurisdictional fires in the western United States.

Methods

Models

Generally, the tested models include geomorphic parameters that describe the physical watershed including size, slope, or lengths (table 1). Typically, forcing data includes precipitation, storm intensity, or storm duration. In the current study, smaller basins (less than 13 square kilometers [< 13 km^2]) are modeled as lumped (basin inputs and parameter are uniform) and larger watersheds are distributed (basin inputs and parameters vary by subbasin). In both cases, modeled basin outputs include either peak discharge or a complete discharge hydrograph at the outlet. After prefire models are established, models are altered using published literature or documentation to create postfire models. It is important to note that the tested hydrologic models do not include algorithms for sediment or debris bulking factors. Bulking factors increase the clearwater discharge to represent the high concentrations of sediment typical of postfire conditions (Gusman et al. 2009).

Rowe Countryman and Storey

The Rowe Countryman and Storey is a method for estimating flood peaks and erosion for basins within the national forests of southern California (Rowe et al. 1949). The Rowe Countryman and Storey establishes reasonable estimates through detailed look-up tables of the average frequency and size of peak flow events and erosion rates associated with normal (unburned) conditions, the effect of burned vegetation, and the recovery of vegetation and hydrology with respect to time. Rowe et al. (1949) undertook extensive observations across southern California watersheds (along the coast from the Mexican border to San Luis Obispo) and developed relations for peak discharge frequencies for over 250 watersheds within 5 zones. Relations were then established between storm precipitation and postfire peak discharge for watersheds in each specific storm zone and determined the changes in these flows for subsequent postfire years. The method is still widely used for runoff estimates in southern Californian watersheds.

Table 1—Summary of models utilized in the current study, including model developer, platform for application, constraints on watershed size, and model outputs

Model	Creator	Platform	Most suitable watershed size	Outputs
RCS	Rowe Countryman Storey	Look up tables (LUTs)	N/A	Q_{pk}, sediment
USGS Linear Regression	USGS	Regional USGS regression eqns	>13 km^2	Q_{pk}
		Curve Number (CN) Methods		
TR-55	USDA NRCS	WinTR-55	<65 km^2	Q_{pk} and time, hydrograph
Wildcat 5	USFS, Stream Team, Fort Collins, CO	Microsoft Excel macros (2003 or later)	<13 km^2	Q_{pk} and time, hydrograph
USACE HEC-HMS	U.S. Army Corps	Windows	Flexible	Storm hydrograph, Q_{pk} and time

The USGS Linear Regression Equations are developed for estimating 2-, 5-, 10-, 25-, 50-, and occasionally 100-year peak discharge for ungauged sites across the United States, generally for prefire conditions. The least squares regression equations are produced for broad regions using long-term discharge observations. In the current study we implement regression equations previously developed for Region 14 (Arizona), Sierra (California), South Coast (California), Mountain (Colorado), Upper Yellowstone Central Mountain (Montana), and Region 4 (Washington). The general regional equations and variables used in this study are outlined below (coefficients provided in table 2; formulas developed for English units):

Region 14, Arizona (Thomas et al. 1997):
$Q_t = kA^a(E/1000)^b$

Sierra, California (Waananen and Crippen 1977): $Q_t = kA^aP^bH^c$

South Coast, California (Waananen and Crippen 1977): $Q_t = kA^aP^b$

Mountain, Colorado (Vaill 2000):
$Q_t = kA^a(S+1)^b$

Upper Yellowstone-Central Mountain, Montana (Omang 1992):
$Q_t = kA^a(E/1000)^b(HE+10)^c$

Region 4, Washington (Sumioka et al. 1998):
$Q_t = kA^aP^b$

where: t = recurrence interval, A = watershed area (square miles) [mi^2], P = mean annual precipitation [in], H = altitude index (average of elevations at points 10 percent and 85 percent along the channel in thousands of feet[ft]), E = mean basin elevation [ft], S = slope, and HE = basin high elevation index (percentage of the total basin area above 6,000 ft).

The CN approach was developed by the U.S. Department of Agriculture Natural Resources Conservation Service (NRCS) to estimate runoff volume primarily from agricultural settings (U.S. Department of Agriculture, Soil Conservation Service [SCS] 1991). The Soil Conservation Service CN method considers rainfall, hydrologic soils, land cover type, treatment and conservation practices, hydrologic conditions, and topography. The selected CN value is a function of land cover type, soil properties, and antecedent moisture conditions, which can be estimated from look-up tables or geospatial data sets. The SCS method considers four hydrologic soil groups (A, B, C, and D), categorized table 2 by similar physical structure, texture, infiltration and runoff characteristics (i.e., degree of swelling when saturated, transmission rate of water) (U.S. Department of Agriculture, Natural Resources Conservation Service 2007). Soil group runoff potential increases from low (A) to high (D) and decreases from free water transmission (A) to restricted water transmission (D). The TR-55 models accommodate three predefined rainfall distributions types—Type I, IA, and III, which are based on climate zones across the United States (U.S. Department of Agriculture, Natural Resources Conservation Service 2009) (table 6). Type I and IA represent the Pacific maritime climate (wet winters and dry summers). Type IA is the most gradual rainfall distribution type and Types II and III represent similar distributions of intense, short-duration rainfall.

Table 2—U.S. Department of the Interior, U.S. Geological Survey Linear Regression Models and coefficients for prefire conditions (developed for English units) for each recurrence interval used in the current study, where t = recurrence interval, A = watershed area [mi2], P = mean annual precipitation [in], H = altitude index (average of elevations at points 10% and 85% along the channel in thousands of feet), E = mean basin elevation [ft], S = slope, and HE = high elevation index (percentage of the total basin area above 6,000 ft)

State	Region		Equation	t=2	t=5	t=10	t=25	t=50
Arizona	Region 14	Frye	$Q_t = kA^a(E/1000)^b$	k=0.124 a=0.845 b=1.44	k=0.629 a=0.807 b=1.12	k=1.43 a=0.786 b=0.958	k=3.08 a=0.768 b=0.811	k=4.75 a=0.758 b=0.732
California	Sierra	Bull #3, Rock	$Q_t = kA^aP^bH^c$	k=0.24 a=0.88 b=1.58 c=-0.80	k=1.20 a=0.82 b=1.37 c=-0.64	k=2.63 a=0.80 b=1.25 c=-0.58	k=6.55 a=0.79 b=1.12 c=-0.52	k=10.4 a=0.78 b=1.06 c=-0.48
California	South Coast	Arroyo, Devil	$Qt = kA^aP^b$	k=0.14 a=0.72 b=1.62	k=0.40 a=0.77 b=1.69	k=0.63 a=0.79 b=1.75	k=1.10 a=0.81 b=1.81	k=1.50 a=0.82 b=1.85
Colorado	Mountain	Hayman	$Q_t = kA^a(S+1)^b$	k=11.0 a=0.663 b=3.465	k=17.9 a=0.677 b=2.739	k=23.0 a=0.685 b=2.364	k=29.4 a=0.695 b=2.004	k=34.5 a=0.700 b=1.768
Montana	Upper Yellowstone Central mountain	Fridley	$Q_t = kA^a (E/1000)^b (HE+10)^c$	k=0.177 a=0.85 b=3.57 c=-0.57	k=0.960 a=0.79 b=3.44 c=-0.82	k=2.71 a=0.77 b=3.36 c=-0.94	k=8.54 a=0.74 b=3.16 c=-1.03	k=19.0 a=0.72 b=2.95 c=-1.05
Washington	Region 4	An-drews	$Q_t = kA^aP^b$	k=0.025 a=0.880 b=1.70	N/A	k=0.179 a=0.856 b=1.37	k=0.341 ta=0.850 b=1.26	k=0.505 a=0.845 b=1.20

The volume of runoff (P_e) is estimated using the CN and cumulative precipitation for a specified duration and the empirical formulation of the uniform loss applied throughout a storm includes (Mays 2001):

$$S = \frac{1000}{CN} - 10 \qquad \text{Equation 1}$$

where: S = Storage (potential maximum retention) and CN = estimated CN value.

$$I_a = (0.1)S \qquad \text{Equation 2}$$

where: I_a = initial abstractions [in] (Baltas et al. 2007).

$$P_e = \frac{(P - I_a)^2}{P - I_a + S} \qquad \text{Equation 3}$$

where: P_e = precipitation excess (runoff depth) [in] and P = total storm precipitation [in].

For consistency, the SCS Dimensionless Unit Hydrograph (UH), an empirical method used to route flow to a designated output location or design point, is selected for use in the Wildcat 5, TR-55, and the HEC-HMS models. The SCS UH method uses time of concentration, T_c, which is defined as the time for a particle of water to travel from the furthest point of the watershed to the design point (U.S. Department of Agriculture Soil Conservation Service 1991; Mays 2001):

$$T_c = \frac{L^{0.8}(S+1)^{0.7}}{1140\,(Y^{0.5})} \qquad \text{Equation 4}$$

where: T_c = time of concentration [hours], L = watershed length [ft], and Y = average watershed slope [%]. Lag time is subsequently defined as:

$$T_L = 0.6T_c \qquad \text{Equation 5}$$

where: T_L = lag-time [hours]; which is the time from the center of mass of rainfall to the time of peak discharge. The time to peak (T_p) is defined as:

$$T_p = 0.67T_c \qquad \text{Equation 6}$$

where: T_p = time to peak [hours]; which is the time from the beginning of rainfall to the time of peak discharge. Base time (T_b) is defined as:

$$T_b = 2.67T_p \qquad \text{Equation 7}$$

where: T_b = base time [hours]; which is the duration of the storm response. Finally, peak discharge (Q_p) is defined as:

$$Q_p = 484\,\frac{A}{T_p} \qquad \text{Equation 8}$$

where: Q_p = peak discharge [cfs] and A = area [mi^2].

Wildcat 5

The Wildcat 5 is used extensively in Forest Service applications to wildlands (Hawkins and Munoz 2011) and is applicable to watersheds less than 13 km^2. The model is spreadsheet based (Microsoft Office Excel 2003 or later) whose inputs include storm characteristics, watershed soil and cover (to calculate runoff depths), timing parameters (related to time of concentration), and unit hydrograph selection. The outputs include a calculated hydrograph and peak runoff (Hawkins and Munoz 2011).

TR-55

TR-55 is typically run for small watersheds (< 65 km^2) and is capable of accommodating up to 10 homogenous subbasins. The model calculates storm runoff volume, peak flow rate, hydrograph, and storage volume for storm water management (U.S. Department of Agriculture Natural Resources Conservation Service 2009). Storm data required by TR-55 includes: rainfall return period [year], 24-hour rainfall amount [tinch], and rainfall distribution type (function of rainfall intensity). The TR-55 uses the Muskingum-Cunge for routing with time of concentration manually inputted

or calculated using the following parameters: length [ft], slope [ft/s], surface (Manning's n), and velocity [ft/s], for sheet, shallow concentrated, and channel flow types. Using the U.S. Department of Commerce National Oceanic and Atmospheric Administration Atlas of Precipitation to determine 24-hour storm depths for each recurrence interval, the TR-55 outputs corresponding peak streamflow values. The program is available to download for free from <http://www.wsi.nrcs.usda.gov/products/W2Q/H&H/tools_models/wintr55.html>.

HEC-HMS

The HEC-HMS is a modular framework developed by the U.S. Army Corps of Engineers. The CN is one of several available methodologies that can be used to simulate precipitation-runoff processes based on physiographic data within watershed systems. The model can be used to simulate observed events over a system (user-defined meteorological forcing) or to simulate predefined design storms. The HEC-HMS has a more complex graphical user interface than other tested models, however the modeling framework includes options for numerous physical configurations of a watershed (i.e. subbasin, reach, junction), subbasin loss methods (Soil Conservation Service CN selected for this study), runoff transformation methods (Soil Conservation Service unit hydrograph selected), and open channel routing methods (Muskingum-Cunge selected) (U.S. Army Corps of Engineers 2010). The HEC-HMS model also has options to include baseflow in runoff prediction. The program is available to download for free from <http://www.hec.usace.army.mil/software/hec-hms/index.html>.

Postfire Modifiers

To simulate postfire conditions, model parameters are adjusted to reflect changes in watershed properties.

Rowe Countryman and Storey

Look-up tables for the (RCS) method incorporate postfire peak flow and erosion rates for time intervals up to 70 years after fire.

USGS Linear Regression Equations

The U.S. Geological Survey uses estimated modifiers to scale prefire runoff values to postfire runoff values (Foltz et al. 2009). The modifier is a function of the soil burn severity and a parameter that accounts for increased runoff. The prefire Q_n is then multiplied by the modifier to produce an estimate of postfire runoff for each return interval. There are no standard guidelines to determine postfire modifiers; BAER team members utilize their own methods, varying by region, model, or modeler (Foltz et al. 2009). For this study the modifier is calculated using Foltz et al. (2009):

$$\textit{Modifier} = 1 + \left[(\%\textit{RO}_{\textit{increase}}) * \frac{(A_H + A_M)}{A_T} \right] \qquad \text{Equation 9}$$

where: A_H = Area of high soil burn severity [mi^2], A_M = Area of moderate soil burn severity [mi^2], A_T = total watershed area [mi^2], and percent $RO_{increase}$ = percent of runoff increase, postfire [%].

Methods for estimating the percent runoff increase for the postfire year have not been well defined. In the current study, the percent runofft increase is estimated using long-term (over 40 years) streamflow records, BAER reports, or previously published studies (Benavides-Solorio and MacDonald 2001; Biddinger et al. 2003; Brandow et al. 2003). Regional watersheds with pre- and postfire discharge records (Frye Creek, AZ (USGS gauge 9460150), Arroyo Seco, CA (USGS gauge 11098000), Devil Canyon, CA (USGS gauge 11063680), and Andrews Creek, WA (USGS

gauge 12447390)) were used to estimate a percent runoff parameter for the current study. The a priori estimation of the percent runoff parameter has significant influence on the final postfire modifier and poor definition of this value ultimately results in higher uncertainty in postfire predictions. Reducing the uncertainty in the modifier is outside the scope of this study, but is a subject for future investigation.

Curve Number Models

To adjust the CN parameter for postfire land cover conditions, the following guidelines (Higginson and Jarnecke 2007) are utilized (note that the maximum CN value is 100):

Low soil burn severity CN = prefire CN + 5	Equation 10
Moderate soil burn severity CN = prefire CN + 10	Equation 11
High soil burn severity CN = prefire CN + 15	Equation 12

The adjusted postfire CN decreases the time of concentration parameter, resulting in faster routing of peak discharge through the affected basins.

Data Resources and Parameters

A range of parameters are necessary for pre- and postfire model development. These parameters often are estimated using various methods (regional topographic maps, geospatial data, local knowledge, and so forth) and implemented into models to predict peak flow events. Electronic databases provide objective and readily accessible tools for the acquisition of relevant model parameters (table 3). A digital elevation map can be utilized to determine contributing watershed area, basin geophysical characteristics (slope, slope aspect, or lengths), and stream features, and are acquired from the U.S. Geological Survey <http://viewer.nationalmap.gov/viewer/>. Land cover classification is used to estimate prefire land cover and is provided by the U.S. Geological Survey <http://www.mrlc.gov/finddata.php>. National Land Cover datasets (2001 and 2006) are 16-class land cover products

Table 3—Web sites with relevant databases used to obtain pre- and postfire model parameters and input data

Electronic Resources	Source	Parameters
Digital Elevation Map	USGS Digital Elevation Map <http://viewer.nationalmap.gov/viewer/>	Geophysical parameters; routing
Land cover	National Land Cover Database (2001 and 2006) <http://www.mrlc.gov/finddata.php>	Curve number
Soil classification	USDA Natural Resources Conservation Service <http://websoilsurvey.nrcs.usda.gov/app/HomePage.htm>	Curve number
Design Storms	National Oceanic and Atmospheric Administration <http://hdsc.nws.noaa.gov/hdsc/pfds/index.html>	Precipitation Frequency
Climate	National Climate Data Center <http://gis.ncdc.noaa.gov/map/viewer/#app=cdo>	Precipitation
Burned Area Reflectance Classifications	Remote Sensing Applications Center <http://www.fs.fed.us/eng/rsac/baer/>	Soil burn severity

across the United States with 30 meter spatial resolution. The classification is developed from the unsupervised Landsat Enhanced Thematic Mapper+ (ETM+) satellite data. The U.S. Department of Agriculture Natural Resources Conservation Service provides a Web Soil Survey for the contiguous United States <http://websoilsurvey.nrcs.usda.gov/app/HomePage.htm>. Soil type is used to establish model infiltration parameters and the partitioning between incoming precipitation and surface runoff.

Soil burn severity, required for postfire CN adjustment, is a representation of the boundary and degree of burn within a wildfire (Key and Benson 2004). Digital soil burn severity maps typically are generated from remote sensing products such as Landsat and are validated in situ by BAER teams. The validated maps are known as Burned Area Reflectance Classification maps and can be acquired from a remote sensing database developed by the USDA Forest Service Remote Sensing Applications Center <http://www.fs.fed.us/eng/rsac/baer/>.

All study models require representation of precipitation amount, frequency, intensity, or duration. Alternatively, a design storm or a representation of the variation of precipitation depth over time can be used. U.S. Department of Commerce National Oceanic and Atmospheric Administration (NOAA) National Weather Service provides the NOAA Precipitation Frequency Estimates at various durations (i.e., 5-min, 10-min, 24-hour, weekly, etc.) and recurrence intervals (i.e., 1-, 2-, 5-, 10-year, etc.) for the United States with 90 percent confidence intervals <http://hdsc.nws.noaa.gov/hdsc/pfds/index.html>.

Model Application

Model evaluation was undertaken for eight basins in the Western United States for both pre- and postfire conditions; four of the basins have prefire observational USGS peak discharge (table 4). The study sites are located within Arizona, California, Colorado, Montana, and Washington and provide a range of hydroclimatic conditions and varying soil burn severity distribution (table 4-6). Basin sizes range from 0.03 to 57 km^2 (table 4). Frye Creek in southern Arizona was burned by the 2004 Gibson-Nuttall Complex. Southern California sites include the 2003 Old Fire in the San Bernardino Mountains (Devil Canyon) and the 2009 Station Fire in the San Gabriel Mountains (Arroyo Seco). The northern California sites were burned by the 2010 Bull Fire in southern Sequoia (Bull #3) and the 2008 Butte Lightning Complex (Rock Creek). Andrews Creek in Washington was burned by the 2003 Fawn Peak Complex. Two smaller basins in Colorado and Montana are analyzed in this study and referred to by the name of the fire that completely burned them (Fridley 2001 and Hayman 2002). The Arroyo Seco is modeled both as lumped and distributed systems with the HEC-HMS model to better represent this larger basin. The three Arroyo Seco subbasins for the distributed model are AS* - Little Bear, AS* - Lower, and AS* - Colby (table 5).

Model Calibration

Prefire models were calibrated to improve peak flow estimations where data were available. Only models whose parameters allow for adjustment are calibrated (TR-55 and HEC-HMS). Parameters dependent on the CN are adjusted to better match prefire observations using statistics and visual inspection of hydrographs. Calibration efforts focus primarily on matching peak discharge, with a secondary focus on discharge volume. The TR-55 is

Table 4—General basin characteristics, including nearest city/State, fire name and year, latitude and longitude of basin outlet, area, outlet elevation, basin slope, and dominant prefire vegetation (arranged by basin size)

Study Site	Location; nearest city	Fire, year	Outlet [°lat., °long.]	Area [km^2]	Outlet elev. [m]	Slope [%]	Pre-fire dominant vegetation	Burn Severity [%]
Andrews Creek*	Northern WA; Mazama	Fawn Peak Complex, 2003	48.823, -120.146	57	1304	15	forest/ shrubland•	13 (L) 22 (M) 14 (H)
Arroyo Seco*	Southern CA; La Canada	Station, 2009	34.222, -118.177	40	426	6	shrubland/ forest†	14 (L) 66 (M) 13
Devil Canyon*	Southern CA; San Bernardino	Old, 2003	34.208, -117.331	14	634	15	shrubland/ forest•	6 (L) 31 (M) 63 (H)
Frye Creek*	Southern AZ;Thatcher	Gibson-Nuttall Complex, 2004	32.744, -109.838	10	1696	22	forest•	25 (L) 42 (M) 20 (H)
Bull #3	Southern Sequoia, CA; Kernville	Bull, 2010	35.835, -118.46	4.12	893	52	shrubland/ forest†	13 (L) 68 (M) 3 (H)
Rock Creek	Northern CA; Storrie	Butte Lightning Complex, 2008	39.905, -121.345	0.69	578	45	shrubland/ forest†	40 (L) 40 (M) 1 (H)
Fridley	Southern MT; Emigrant	Fridley, 2001	45.51, -110.78	0.13	1930	43	shrubland/ herbaceous•†	0 (L) 0 (M) 100 (H)
Hayman	Central CO; Woodland Park	Hayman, 2002	39.18, -105.36	0.03	2440	33	forest•	0 (L) 0 (M) 100 (H)

**denotes available observational prefire USGS peak discharge*

•Homer et al. 2004 (National Land Cover Database 2001)

†Fry et al. 2011 (National Land Cover Database 2006)

Table 5—Summary of pre- and postfire CN model parameters used in the Wildcat 5, TR-55, and HEC-HMS models

		Prefire		Postfire		
Watershed	**Hydrologic Soil Type**	**Curve Number**	**T_c [hr]**	**Curve Number**	**T_c [hr]**	**% RO**
Andrews Creek	B	59	5.51	64	4.85	34
Arroyo Seco	C	72	5.14	81	3.94	50
AS* - Little Bear	D	71	1.99	78	1.63	N/A
AS* - Lower	C	73	4.33	81	3.41	N/A
AS* - Colby	C	73	2.69	80	2.19	N/A
Devil Canyon	C	73	2.09	86	1.39	121
Frye Creek	B	58	2.61	66	2.13	83
Bull #3	D	82	0.49	90	0.37	147
Rock Creek	D	79	0.33	85	0.27	66
Fridley	B	74	0.17	89	0.11	100
Hayman	D	79	0.14	94	0.08	20

AS indicates one of three subbasins of the Arroyo Seco used in the distributed models*

Table 6—Uncalibrated (Uncal) and calibrated (Cal) parameters for Arroyo Seco lumped and distributed models (the distributed model consist of three subbasins denoted with AS). Storm 1 and Storm 2 identify the storms utilized in this study

TR-55	Type	CN	T_L[hr]	T_c [hr]	I_a [cm]
Lumped	Uncal	72	---	5.14	---
	Cal	51	---	6.80	---
HEC-HMS					
Lumped	Uncal	72	6.17	10.28	0.99
	Cal Storm 1	45.5	3.17	5.28	10.39
	Cal Storm 2	35.25	5.25	8.75	10.80
AS - Colby	Uncal	73	1.61	2.69	1.88
	Cal Storm 1	21	2.08	3.47	8.13
	Cal Storm 2	21	2.33	3.89	7.87
AS - Little-Bear	Uncal	71	1.19	1.99	2.08
	Cal Storm 1	21	2.67	4.44	7.62
	Cal Storm 2	21	1.67	2.78	7.87
AS - Lower	Uncal	73	2.59	4.32	1.88
	Cal Storm 1	21	6.67	11.11	8.13
	Cal Storm 2	21	3.75	6.25	7.87

calibrated by adjusting the CN until the peak discharge matches for each recurrence interval, while the HEC-HMS model is calibrated by adjusting the CN, Ia, and lag time (table 6). Adjusting the CN also alters the postfire T_c (Equations 1 and 4) and affects the volume and timing of discharge. The calibrated prefire models are then adjusted for postfire conditions using Equations 9 through 14.

We assess prefire model performance for both calibrated and uncalibrated models using flood frequency information from gauged watersheds. The Weibull method commonly is used to analyze streamflow and estimate expected frequency of flows based on the assumption that peak discharge is evenly distributed over a long period of time (Pramanik et al. 2010). The generated discharge values for each recurrence event are considered a reasonable approximation of the associated probability density of discharge values in a basin and allow comparison of modeled design storm simulations to an “observed” storm frequency (Clarke 2002; Pramanik et al. 2010). In the current study, a Weibull frequency distribution is generated using the observed peak flow values for basins where long-term peak discharge exists [Andrews Creek (43-year record), Arroyo Seco (98-year record), Devil Canyon (90-year record), and Frye Creek (33-year record)].

To evaluate performance, we utilize two commonly used metrics, root mean square error and percent bias:

$$\textit{Root Mean Square Error} = \frac{\sqrt{\sum_{i=1}^{n} (Q_{model} - Q_{obs})^2}}{n} \qquad \text{Equation 13}$$

where: n = number of Q_{pk} events for each model.

$$\textit{Percent Bias} = \frac{Q_{model} - Q_{obs}}{Q_{obs}} * 100\% \qquad \text{Equation 14}$$

where: Q_{model} = modeled discharge at a specific recurrence interval, and Q_{obs} = observed discharge (either Weibull).

Model Assessment

Pre- and Postfire Peak Discharge

Models are applied to the eight study basins considering model and regional constraints (table 7). Models are initially run uncalibrated and for prefire conditions and then adjusted for postfire prediction using modifiers or established methods. We also undertake calibration for the Arroyo Seco and Devil Canyon basins, where 15-minute discharge is available, and use the calibrated models to predict postfire runoff. Pre- and postfire modeled peak discharge for 2-, 5-, 10-, 25-, and 50-year (Q_2, Q_5, Q_{10}, Q_{25}, and Q_{50}) recurrence intervals are normalized by basin area to evaluate performance across all eight study basins.

Uncalibrated model predictions across the sites (peak discharge/unit area) are highly variable under both pre- and postfire conditions (figure 1). For prefire conditions, the models underpredict the estimated peak discharge for Q_2 through Q_{10} at Andrew Creek (figure 1a) and improve for the larger events in this basin. Prefire CN models (TR-55 and HEC-HMS) at Arroyo Seco (figure 1c) and Devil Canyon (figure 1e) overpredict for each peak discharge event. The USGS model also overpredicts at the Q_{25} and Q_{50} events. However, the RCS model performs well across the events when compared to the observed (Weibull estimate) peak discharge. Prefire model predictions at Frye Creek (figure 1g) have the best consistency when compared to the observed peak discharge. Prefire models at the Bull #3

*Table 7—Available pre- and postfire models for each basin, where * indicates observational data is available for prefire model calibrations and ° indicates postfire models adjusted from the calibrated prefire models*

Model	RCS	USGS Linear Regression	TR-55	Wildcat 5	HEC-HMS
Andrews Creek*	—	Pre, Post	Pre, Post	—	Pre, Post
Arroyo Seco*	Pre, Post	Pre, Post	Pre*, Post°	—	Pre*, Post°
Devil Canyon*	Pre, Post	Pre, Post	Pre*, Post°	—	Pre*, Post°
Frye Creek*	—	Pre, Post	Pre, Post	Pre, Post	Pre, Post
Bull #3	—	Pre, Post	Pre, Post	Pre, Post	Pre, Post
Rock Creek	—	Pre, Post	Pre, Post	Pre, Post	Pre, Post
Fridley	—	Pre, Post	Pre, Post	Pre, Post	Pre, Post
Hayman	—	Pre, Post	Pre, Post	Pre, Post	Pre, Post

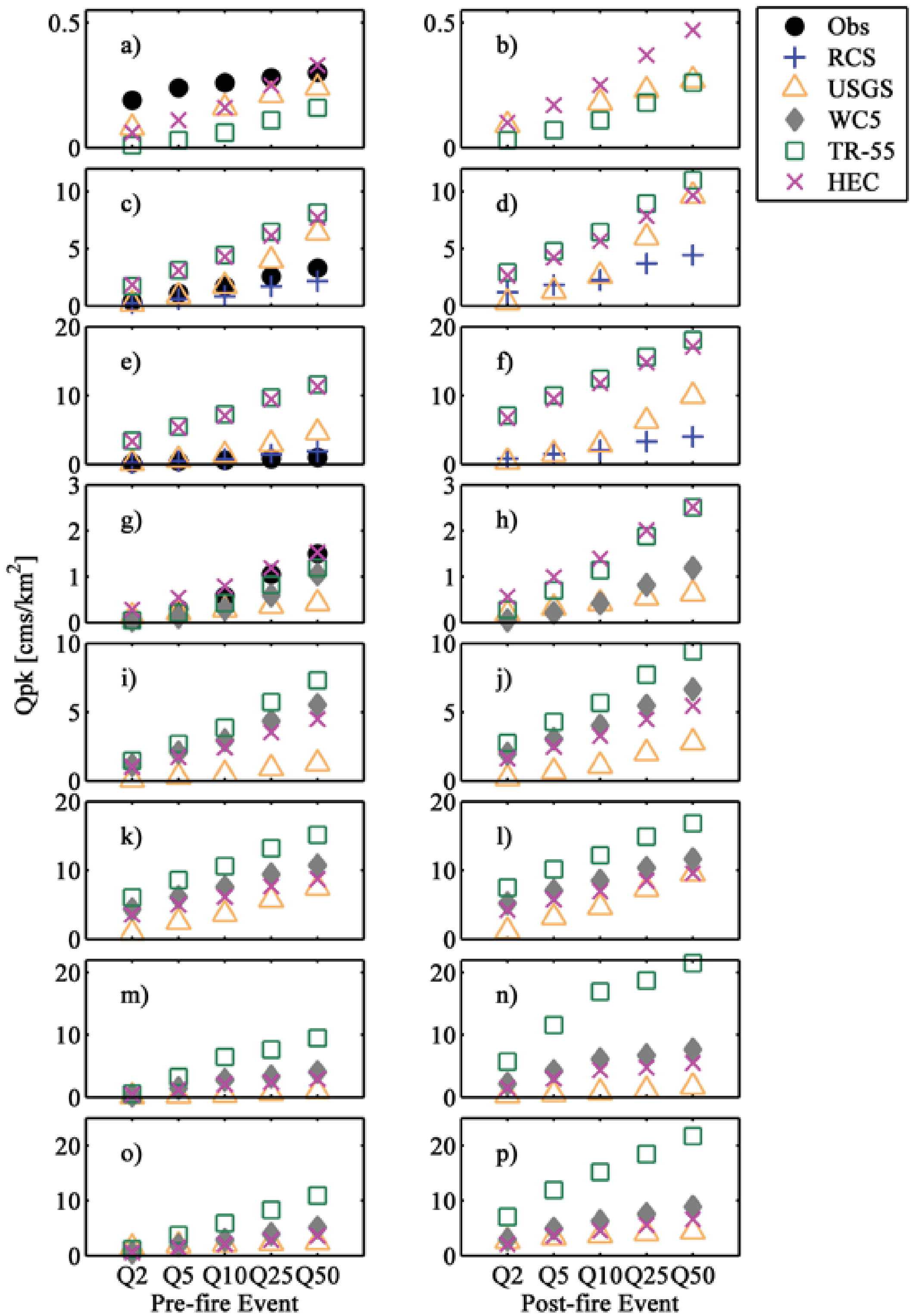

Figure 1—Variability of modeled peak discharge per unit area pre- and postfire for all study basins: Andrews Creek (1a and 1b), Arroyo Seco (1c and 1d), Devil Canyon (1e and 1f), Frye Creek (1g and 1h), Bull #3 (1i and 1j), Rock Creek (1k and 1l), Fridley (1m and 1n), and Hayman (1o and 1p).

(figure 1i), Rock (figure 1k), Fridley (figure 1m), and Hayman (figure 1o) sites show increasing variability between predictions at each recurrence interval, with more spread observed for the larger peak discharge events.

The uncalibrated postfire models show the most discrepancy in peak discharge predictions (figure 1). In general, the smaller and steeper basins (Bull #3, Fridley, and Rock Creek) generate more discharge per unit area (figures 1i through 1p). Andrews Creek is the largest basin with the least amount of burned area relative to all study sites and produces the least amount of discharge per unit area (figures 1a and 1b). The RCS peak discharge predictions are based on in situ observational data, reducing the uncertainty in postfire values. The RCS predictions at the lower recurrence intervals (Q_2 through Q_{10}) correspond well with the USGS regression model (figures 1d and 1f). The USGS regression performs well in the lower recurrence intervals prefire providing more confidence in postfire prediction. The Wildcat 5 generally has simulations in the middle of the ensemble of predictions, suggesting better overall performance relative to the other models (figures 1f, 1l, and 1n). At Fridley and Hayman, the TR-55 is highly incongruous with the other models (figures 1n and 1p). At Rock Creek, all the CN models are inconsistent with the USGS regression model (figure 1l). The inconsistency between model predictions, especially notable in the smaller watersheds, contributes to the uncertainty in model prediction and highlights the discretion necessary for model selection.

Curve Number Model Parameter Sensitivity

Simulated peak discharge (per unit area) appears strongly influenced by watershed characteristics but shows significant variability between models (figure 2). The TR-55 is highly sensitive to model parameters, while the RCS and USGS methods appear least sensitive to basin characteristics. Slope (figure 2b), soil type (figure 2e), and CN (figure 2f) have the most influence on prefire model predictions. In the CN models, slope influences the time of concentration; with steeper slopes equating to smaller residence time within the basin. The shorter time of concentration values produce more immediate discharge, especially under postfire conditions. Under postfire conditions, the CN (figure 2m) and percent of the basin burned (figure 2o) have significant influence on modeled discharge. Rainfall distribution, determined by site location and used as input to the USGS and CN models (table 8), also influences the predicted discharge. Some of the California watersheds are on the boundary between NRCS Type I and IA rainfall distribution types. The Type IA rainfall distribution (Bull #3) results in a larger runoff response. This is extremely pronounced in the Q_{25}, Q_{50} during prefire conditions, and for all postfire events (figures 1e and 1f). Similarly, the CN significantly influences the overall volume of predicted runoff (lower CN decreases discharge volume; higher CN increases discharge volume). Both parameters are somewhat subjective and contribute to model uncertainty due to the inconsistencies in CN acquisition and rainfall distribution type.

Soil classification has more of an influence on prefire discharge (figure 2e) than postfire discharge (figure 2l). The California and Hayman sites are generally characterized by soil types C (Arroyo Seco and Devil Canyon) and D (Bull Fire, Hayman, and Rock Creek), which generate moderate and high runoff potential, respectively. In both soil groups, C and D, water transmission is restricted. Fridley and Frye Creek are characterized by soil type B, defined as moderately low runoff potential and unimpeded water transmission. Under immediate postfire conditions, surface soils are highly hydrophobic and contribute to increased

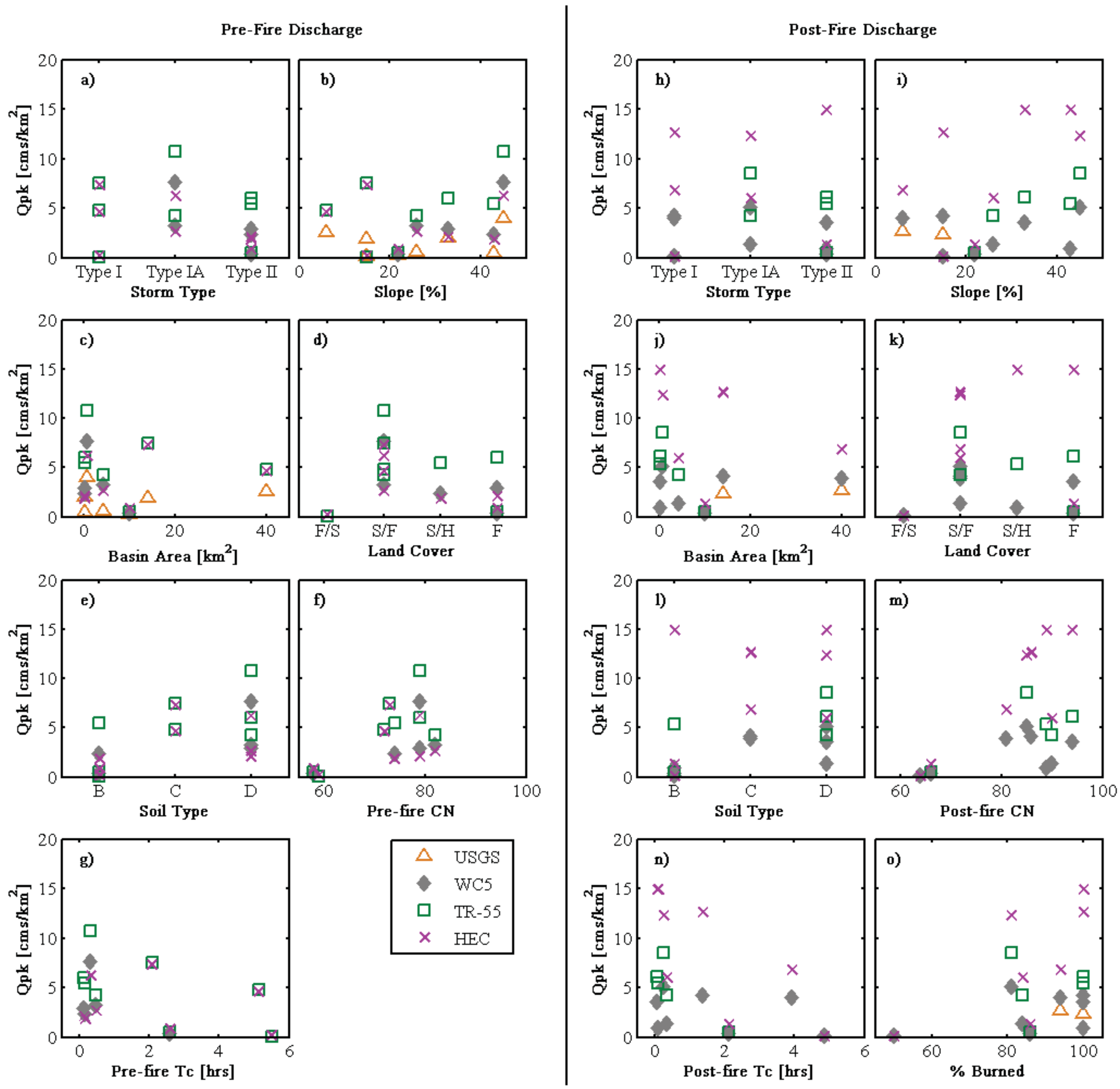

Figure 2—Pre- and postfire peak discharge per unit area with respect to model variables. Storm type (2a and 2b) is from the NRCS rainfall distribution types. Land cover (2d and 2k) is from the USGS National Land Cover datasets (2001 and 2006), where "F/S" is predominantly forest and shrubland, "S/F" is predominantly shrubland and forest, "S/H" is predominantly shrubland and herbaceous, and "F" is predominantly forest. The hydrologic soil type (2e and 2l) is from the USDA Natural Resources Conservation Services Web Soil Survey.

runoff. Breakdown of the hydrophobic layer is dependent on amount and intensity of rainfall (DeBano 2000). Postfire CN parameters are simply modified (Higginson and Jarnecke 2007; Cydzik and Hogue 2009) to reflect an increase in immediate surface runoff and a decrease in infiltration.

Table 8—Rainfall distribution type and NRCS 24-hour rainfall frequency distribution for CN models based on regional location

Site	Rainfall Distribution	24-Hour Rainfall Distribution [cm]				
		2-yr	5-yr	10-yr	25-yr	50-yr
Andrews Creek	Type I	4.19	5.08	5.84	6.86	7.62
Arroyo Seco	Type I	12.97	18.08	22.57	29.13	34.54
Devil Canyon	Type I	13.64	17.81	21.20	25.76	29.25
Frye Creek	Type II	5.58	7.02	8.18	9.74	10.95
Bull #3	Type IA	6.78	9.14	11.23	14.34	16.93
Rock Creek	Type IA	15.39	19.38	22.49	26.54	29.34
Fridley	Type II	3.56	5.33	6.86	7.37	8.13
Hayman	Type II	3.30	4.83	5.84	6.86	7.87

Calibration

The TR-55 is calibrated by adjusting the CN parameters until predicted discharge simulates observed peak discharge across recurrence intervals. The HEC-HMS model is calibrated for selected prefire storms (hydrographs) with 15-minute USGS discharge. The lumped and distributed Arroyo Seco design for the HEC-HMS model result in distinct differences for both uncalibrated and calibrated parameters (table 6).The CN significantly decreases and the initial abstractions significantly increase in both the calibrated lumped and distributed models, as a result of having to lower the water volume to match basin rainfall-runoff response. The alteration in CN and initial abstraction reflect sensitivity to soil type and land cover, which govern the transmission of runoff into the soil.

The lag time for the lumped Arroyo Seco and Lower Arroyo Seco subbasin also are lowered to route water more quickly from the upper parts of the basin to the outlet, which more appropriately accounts for the steepness of the watershed (table 6). The lumped and distributed simulations for two observed storms in the Arroyo Seco (Storm 1: 24–28 December 2003 and Storm 2: 19–26 October 2004) show significant improvement after calibration (figures 3b and 3d (uncalibrated) versus figures 3a and 3c (calibrated)). The observed discharge is greatly overestimated by the uncalibrated lumped and uncalibrated distributed hydrographs for each storm (figures 3a and 3c). The calibrated distributed model is better able to capture the peak and volume of the observed storm than the lumped model. The October 2004 storm, which has a dual peak, had simulations that did not adequately match the observed discharge (figure 3d). The second pulse of precipitation is difficult to capture, and both models overpredict discharge response. Overall, the distributed calibrated model performs better than the lumped calibrated model (figure 3d).

The final calibrated parameters are evaluated next on two independent storm events (figures 3e and 3f). Simulations generally result in adequate performance for the lumped and distributed models for 28 February–3 March 2006 (Val Storm 1) (figure 3e). A less successful validation is highlighted for a storm occurring 6–11 February 2009 (Val Storm 2) (figure 3f). Both storms indicate that both TR-55 and HEC-HMS are sensitive to precipitation volumes and intensity, which is influenced by the initial abstraction parameter in the model. Overall, the distributed model performs better than the lumped model, demonstrating the influence of including parameter variability throughout the basin. The calibrated models are used next to predict pre- and postfire discharge for Arroyo Seco (figures 4a and 4b) and Devil Canyon (figures 4c and 4d). Prefire, the calibrated peak discharge is significantly less than the uncalibrated discharge (figures 4a and 4c). The calibrated models also generally perform better for Devil Canyon (figure 4c) than in the Arroyo Seco (figure 4a). Uncalibrated models predict significantly more peak discharge postfire, and calibrated TR-55 and HEC-HMS models are more consistent with the RCS and USGS methods (figures 4b and 4d).

Model Uncertainty and Errors

Model errors are highly variable across all basins and fire sites (figure 5). Study models applied to Andrews Creek generally undersimulate (-435 percent to -38 percent bias) (figure 5a). The uncalibrated Q_{25} HEC-HMS (-15 percent), uncalibrated Q_{50} HEC-HMS (14 percent), and Q_{50} USGS (-22 percent) are better and have lower percent bias values (figure 5a). The uncalibrated TR-55 and HEC-HMS models at the Arroyo Seco site have large positive bias, ranging from 133 percent to 611 percent (figure 5b). The RCS method undersimulates at the Arroyo Seco (-52 percent to -34 percent), while bias in the USGS model ranges from -48 percent to 94 percent, showing overprediction in the higher recurrence intervals (figure 5b). The calibrated TR-55 at the Arroyo Seco shows some of the best performance, with percent bias ranging from -7 percent to 26 percent across all events. The lumped and distributed calibrated HEC-HMS models have larger negative bias, ranging from -82 percent to -7 percent (figure 5b). Models at Devil Canyon have the largest spread of percent bias values primarily due to the uncalibrated TR-55 and HEC-HMS predictions (over 1,000 percent bias) (figure 5c). The RCS results in bias values from 25 percent to 88 percent, where Q_{25} and Q_{50} have higher positive bias. The USGS method has lower bias for only the Q_2 event (figure 5c). The calibrated TR-55 and HEC-HMS models significantly reduce percent bias for all peak discharge events in Devil Canyon, especially the Q_2 through Q_{25} events (figure 5c). Models applied to Frye Creek generally show negative bias (figure 5d), with the USGS ranging from -79 percent to 28 percent, and showing the best performance at Q_5 (figure 5d). The Wildcat 5 shows the tightest percent bias range (-33 percent to -5 percent) for all peak discharge events, even though it is an uncalibrated model (figure 5d).

Where observational data is available, the mean root mean square error for each applicable model for Andrews Creek, Arroyo Seco, Devil Canyon, and Frye Creek is computed. The aggregate root mean square error value highlights the overall tendency of models to under- or overpredict peak discharge across the range of recurrence intervals (figure 6). The uncalibrated TR-55 and HEC-HMS have significantly larger error than all available models at each site (figure 6). The TR-55 generally has a lower model error than the HEC-HMS (figures 6b, 6c, and 6d). Andrews Creek and Frye Creek have the lowest root mean square error across all models (figures 6a and 6d).

The mean of all the peak discharge predictions at each site by region highlights overall consistency of model performance (figure 7). The TR-55 model shows the least consistent performance relevant to other applicable models, especially in southern California, northern California, Colorado, and Montana (figures 7a and 7b). The highest consistency among the pre- and postfire model predictions occurs for sites in Arizona and Washington (figures 7a and 7b). The largest discrepancy is observed for northern California and for postfire southern California, Colorado, and Montana (figure 7). There is less agreement between postfire models for southern California, northern California, Colorado, and Montana (figure 7b).

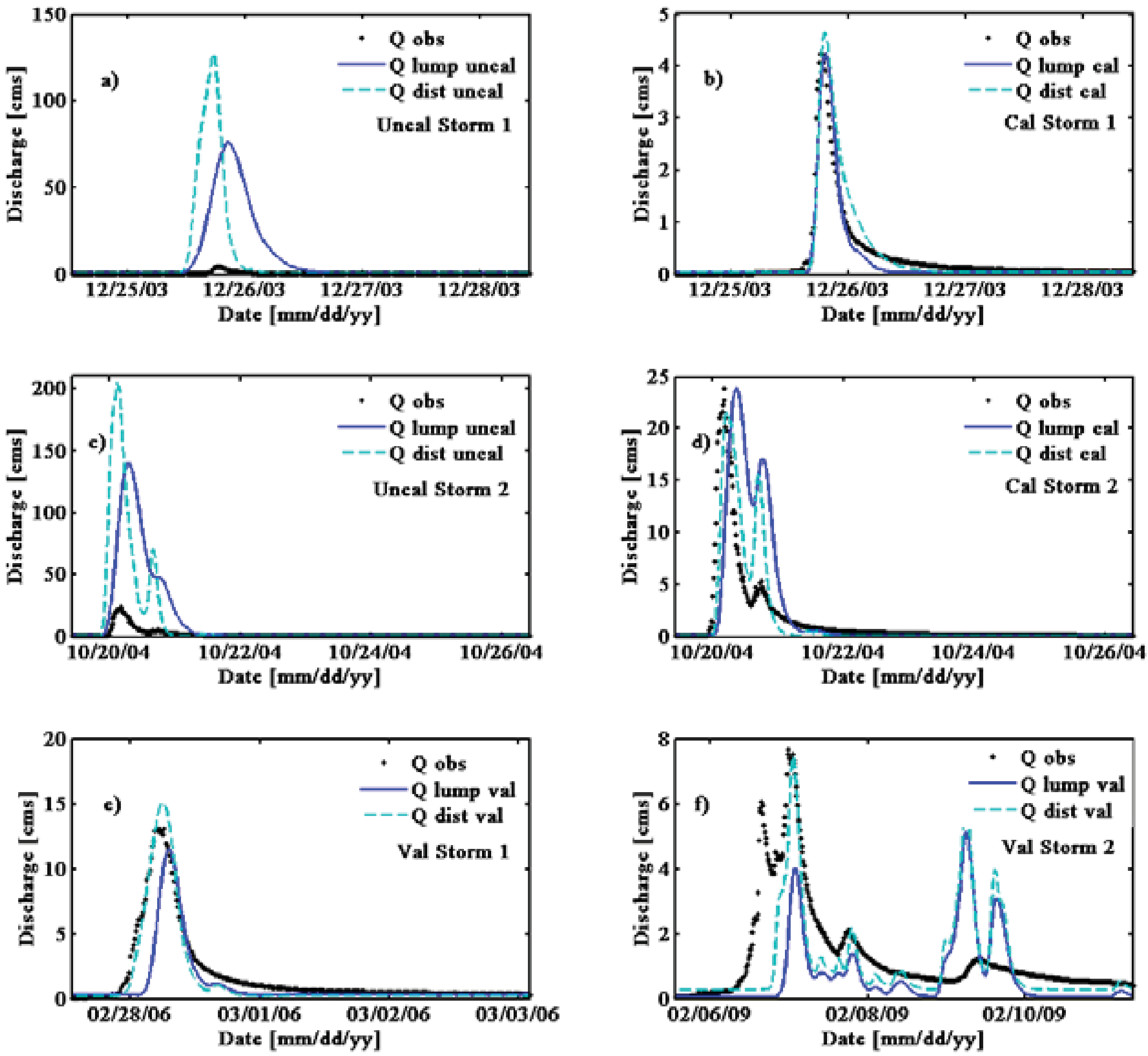

Figure 3—Uncalibrated (3a and 3c) and calibrated (3b and 3d) HEC-HMS lumped and distributed hydrographs for two prefire observed storms in the Arroyo Seco, 25–28 December 2003 (Storm 1) and 20–26 October 2004 (Storm 2). Two validation storms for Arroyo Seco HEC-HMS lumped and distributed models (3e and 3f) for 28 February–3 March 2006 (Val Storm 1) and 6–10 February 2009 (Val Storm 2).

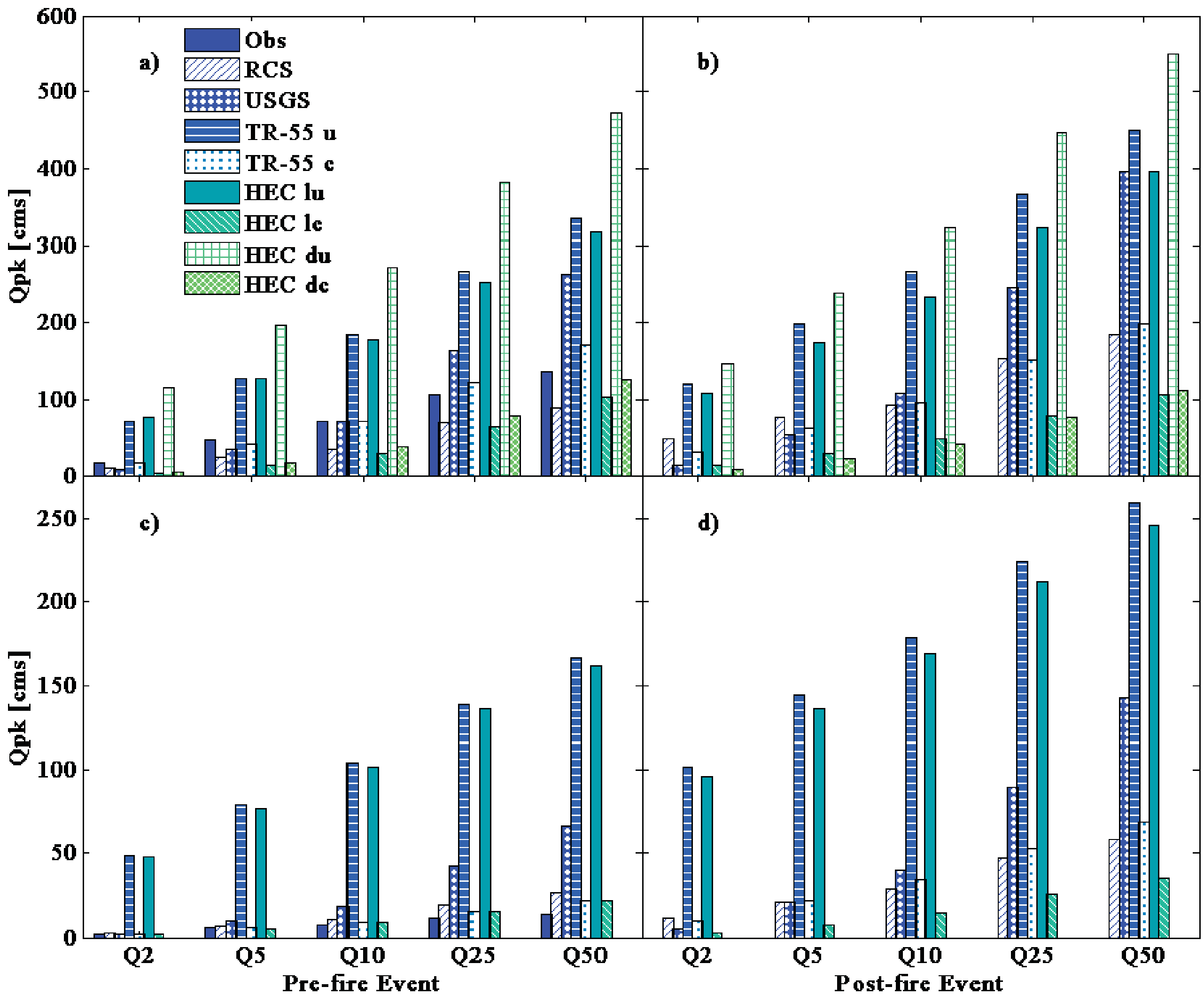

Figure 4—Arroyo Seco (4a and 4b) and Devil Canyon (4c and 4d) pre- and postfire peak discharge per unit area for applicable models (RCS, USGS, TR-55, and HEC). For these basins, TR-55 and HEC include uncalibrated (u) or calibrated (c) models.

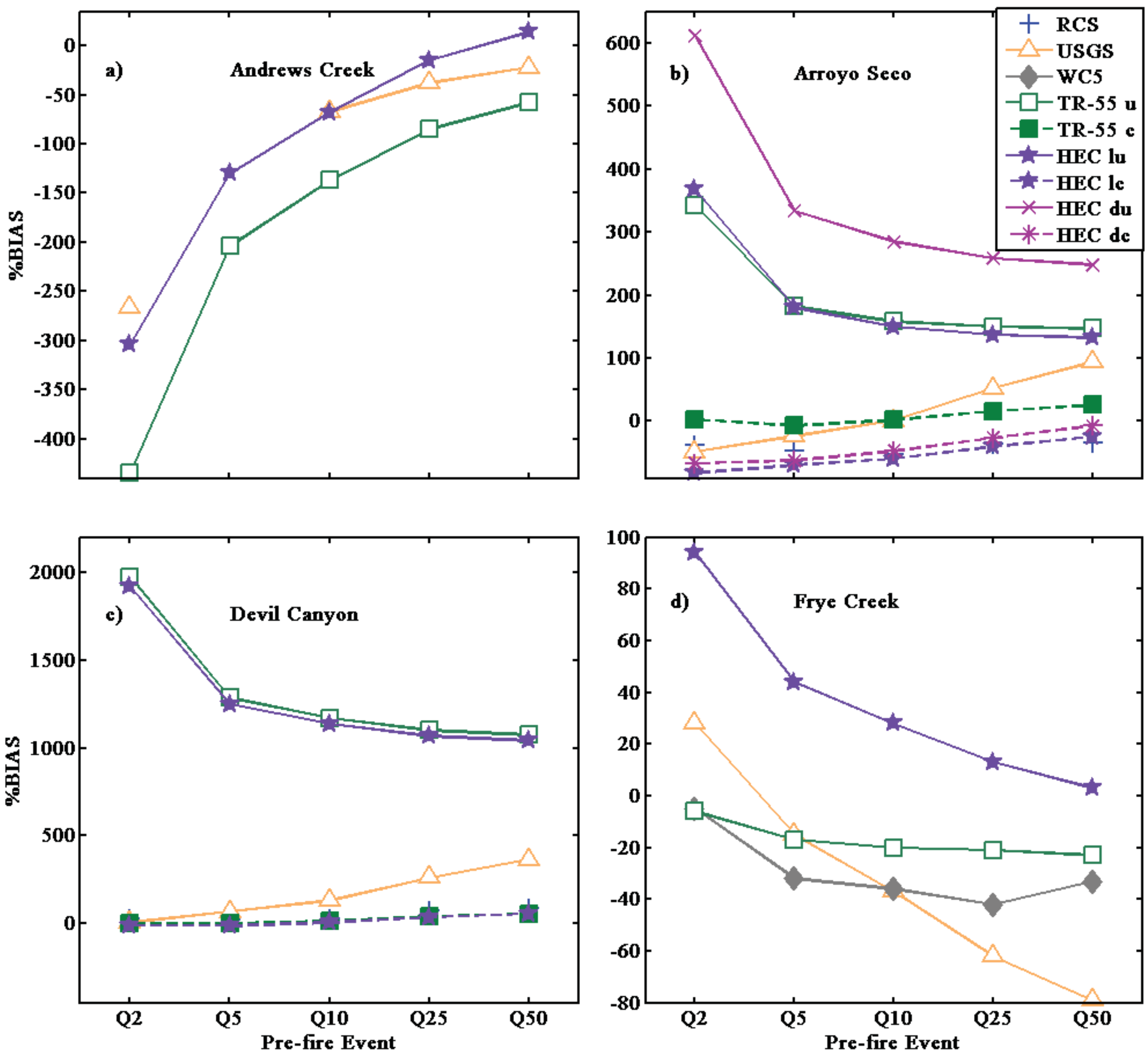

Figure 5—Percent bias for prefire Andrews Creek (5a), Arroyo Seco (5b), Devil Canyon (5c), and Frye Creek (5d) models relative to observational data for each peak discharge event.

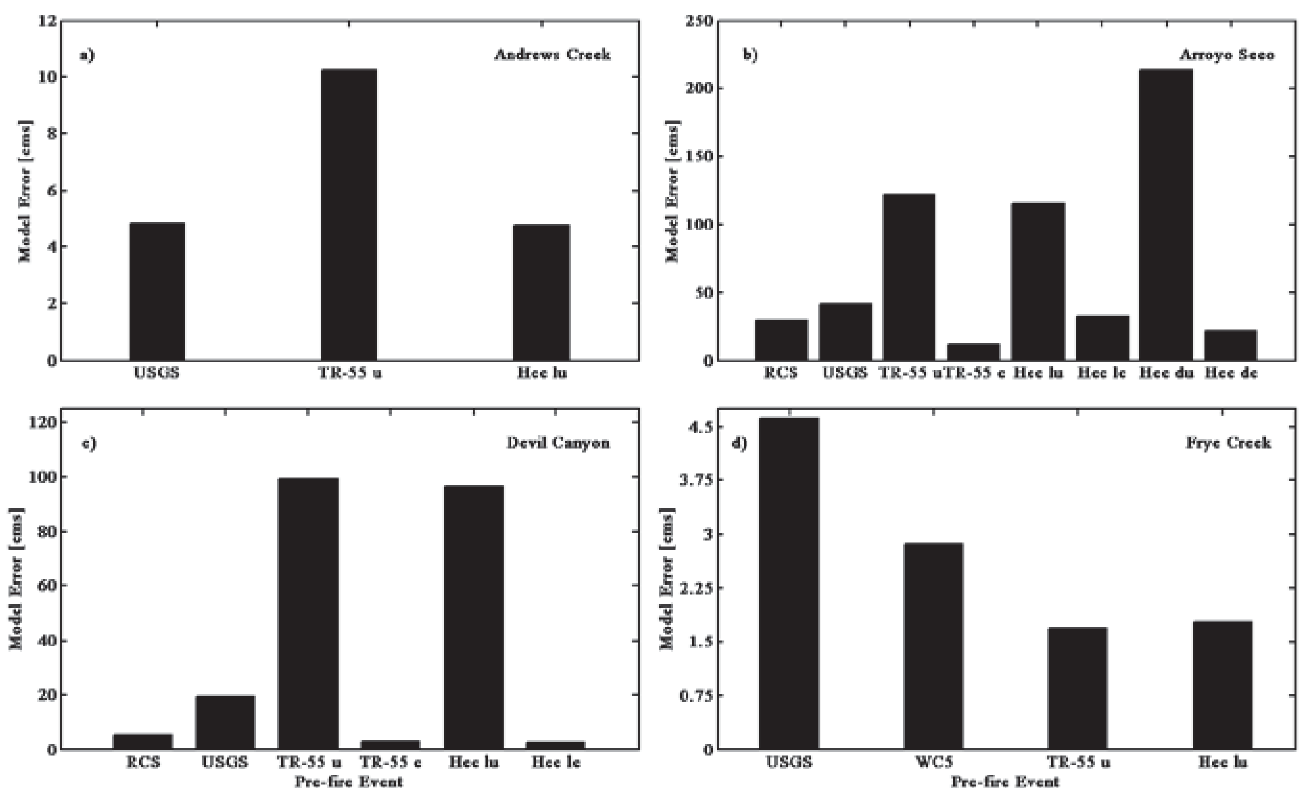

Figure 6—Andrews Creek (6a), Arroyo Seco (6b), Devil Canyon (6c), and Frye Creek (6d) model error across all peak discharge events for available prefire models with observational data, where "u" are uncalibrated, "c" are calibrated, "l" are lumped, and "d" are distributed models.

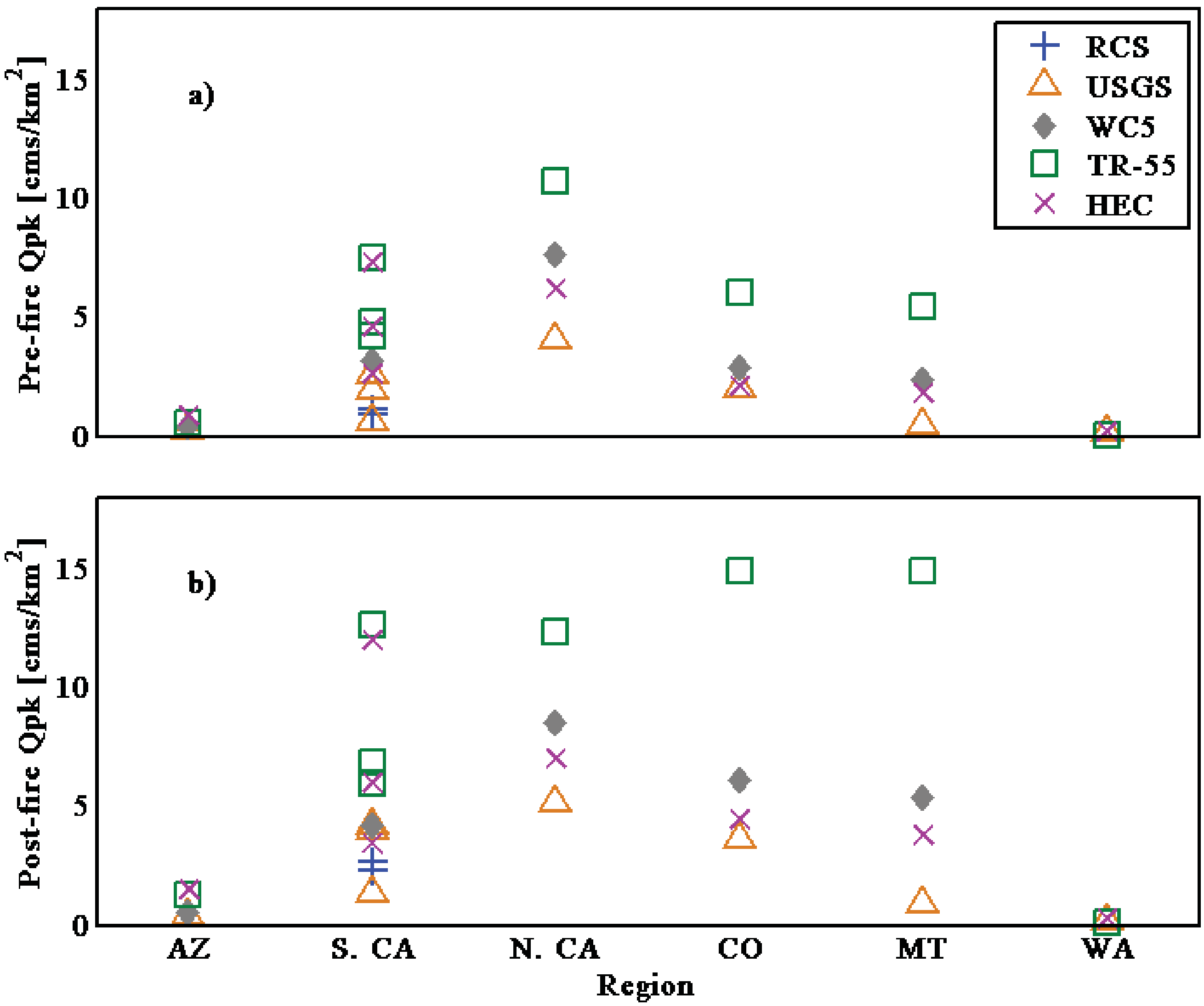

Figure 7—Pre- and postfire (7a and 7b) mean peak discharge per unit area for all models by region (Arizona (AZ), southern California (S. CA), northern California (N. CA), Colorado (CO), Montana (MT), and Washington (WA).

Conclusions

The current study involves systematic evaluation of a range of models commonly used in postfire hydrologic assessments, especially within the operational community. We advocate the implementation of standardized methods to acquire model parameters and transferability of model results from this study to other regions and fires should be used with reservation. In general, results show that discharge estimates are highly variable for the studied watersheds, heavily influenced by climatology (location), geophysical properties, and soil burn severity, and that no single model appears suitable across the range of systems studied. Key insight on model performance is summarized as follows:

- ❒ Estimated peak discharge is highly variable depending on the model and parameter selection within the system.
- ❒ The RCS method performs well as it is based on observational data, but RCS has limited regional applicability (only applicable to southern California). The RCS is also a static model that is not adaptable to changing geomorphology and climate conditions.
- ❒ The USGS linear regression model includes a subjective modifier used to adjust towards postfire peak runoff (requires percent of runoff increase a priori), adding significant uncertainty in discharge estimates. The regional regression equations are broad and not fine-tuned for specific watersheds, resulting in more variable performance.
- ❒ The Wildcat 5 seems to perform the best overall given current methods to acquire CN and without calibration, but application is limited by basin size.
- ❒ The uncalibrated TR-55 tends to overestimate peak discharge events for all watersheds, and has more uncertainty during low-flow events.
- ❒ The HEC-HMS model has a moderate learning curve due to its complex graphical user interface and high number of required parameters, but provides good results after calibration. In addition, the HEC-HMS provides more flexibility for watershed set up (i.e., loss methods, runoff transformations, routing) with user-defined model selections and parameter input.
- ❒ The utilized CN models are sensitive to model parameters such as CN and soil type. Currently a standardized method to acquire and calibrate the CN models does not exist, increasing uncertainty in model results.

For CN models (i.e., TR-55 and HEC-HMS), we recommend that a regional basin be used to calibrate and transfer model parameters to the basin of interest. If sufficient time and data are available to undertake calibration, we recommend use of the HEC-HMS. The model provides the most customizable system, which if used properly, can best reflect watershed behaviors and properties. However, if calibration data or adequate time is not available, the Wildcat 5 is a good choice for watersheds that meet the basin size constraints. Proper selection of a model that works well for the region of study, and can be calibrated, will ultimately improve confidence in postfire flow predictions, reducing management costs and improving regional resource allocation.

Appendix A—BAER Hydrologic Assessment Procedure

This postfire modeling study is intended to provide specialists with additional knowledge of postfire hydrologic modeling assessment by providing a case study with all models previously described in this study. This section is designed to accompany and reinforce the concepts found in the main part of this publication. To evaluate areas of immediate concern, based on expected damage or values at risk, the following concepts, parameters, and steps to monitor areas affected by fire include:

1. Acquire a Burned Area Reflectance Classifications map. Soil burn severity is used to assess the degree to which an ecosystem is altered by fire. The soil burn severity can be determined by various methods. One method quantifies the degree of organic matter lost above the ground by using differenced Normalized Burn Ratio severity levels adapted from Keys and Benson (2004). The Normalized Burn Ratio uses "band math" to estimate differences between pre- and postfire remotely sensed images. The U.S. Department of Agriculture Remote Sensing Applications Center (RSAC) <http://www.fs.fed.us/eng/rsac/baer/> provides Burned Area Reflectance Classifications (BARC) for wildfires. The portal for the data was created by RSAC and the U.S. Department of the Interior, U.S. Geological Survey, Earth Resources Observation and Science to support burned area emergency response (BAER) teams. The BARC data can be downloaded and utilized to guide estimations of soil burn severity for areas of interest. A map that displays the wildfire's impact on the ground surface aids BAER teams in identifying of areas at risk.

2. Validate the BARC map to create a soil burn severity map. BAER teams use BARC images to identify postfire areas at risk; however the BARC is not a soil burn severity map until it has been field verified to better represent ground conditions (Parsons et al. 2010). It is important to produce accurate soil burn severity maps as many postfire treatment decisions rely heavily on this information.

3. Acquire land cover maps or classification. Geographic information systems databases often exist on the city, county, or State level. An accurate representation of the land cover is necessary for estimating the curve number in the Curve Number Method.

4. Acquire soil maps or classification. Geographic information systems databases often exist on the city, county, or State level. The U.S. Department of Agriculture Natural Resources Conservation Service provides a Web Soil Survey <http://websoilsurvey.nrcs.usda.gov/app/HomePage.htm> for the contiguous United States Soil classification is necessary for estimating the curve number in the Curve Number Method. The soil type governs the infiltration rate, influences the partitioning between incoming precipitation and surface runoff.

5. Acquire and integrate road layer or transportation layer for maps with the soil burn severity maps to help assess values at risk.

6. Use a topographic map or digital elevation map to determine a watershed delineation to estimate the contributing area above the value at risk. The maps also can provide

quick assessment of drainage basin boundaries, stream features, such as slope and width, and land features (natural and manmade) in the vicinity of lakes, oceans, and watercourses.

7. Identify values at risk (lives, property, access, natural resources, cultural resources, etc.) and areas for immediate hydrologic assessment. Once the soil burn severity map is overlaid on a map of the area, areas of concern can be identified. High, moderate, and low soil burn severity play key roles in determining values at risk as areas with higher burn may be more susceptible to larger floods and debris flow. Topographic maps offer a wealth of information to the engineer and hydrologist. Many topographic maps show cultural and natural features of an area (including roads, buildings, parks, and legal boundaries) as well as the topography of a region.

8. Determine hydrologic parameters for models.

   a. Climate parameters.

      i. All rainfall-runoff models require some representation of precipitation amount, frequency, intensity, or duration. If rain gauge data is available at a high enough resolution (daily or smaller time step) this can be used to drive a rainfall-runoff model. Alternatively, a design storm—the representation of the variation of precipitation depth with time—can be acquired. A recent project by the U.S. Department of Commerce, National Oceanic and Atmospheric Administration, National Weather Service, the National Oceanic and Atmospheric Administration Precipitation Frequency Estimates for the United States <http://hdsc.nws.noaa.gov/hdsc/pfds/index.html> provides an interactive map that returns precipitation frequencies for various durations (i.e., 5-min, 10-min, 24-hour, weekly, monthly, etc.) and recurrence intervals (i.e., 1-, 2-, 5-, 10-year, etc.) with 90 percent confidence intervals.

   b. Geophysical basin parameters.

      i. A watershed or drainage basin is a geomorphologic (or man made in the case of urban development) structure on the landscape. It consists of all points of land which drain to a common point frequently called the mouth or outlet of the drainage. The watershed is an important concept when considering pre- and postfire flood flows (all area draining to a bridge) and general water resource planning. Because all water in the drainage basin drains to the point of interest, delineation requires simply that one remember water flows downhill. When looking at a topographic map (contour map), water will flow towards the lowest point, always perpendicular to the contours. Ask yourself, “If I were a raindrop landing at this point, where would I flow?” You should be able to determine whether that raindrop flows from any starting location through the outlet. If it does not flow through the outlet, the starting point is not in the drainage basin. Typical methods of delineating and estimating the area of a basin includes Autocad, geographic information systems, planimeters, or counting squares.

ii. Channel length is the distance measured along the main channel from the outlet to the end of the channel. It is rarely a straight line.

iii. Watershed length is the distance measured along the main channel from the outlet to the basin divide (extending the channel length to the topographic ridge). It is the longest length or travel path and is rarely a straight line. It is used to compute travel time parameters.

iv. Altitude index is the average elevation along 10 percent and 85 percent of the watershed length. This value is utilized in thousands of feet.

v. Watershed slope is the change in elevation between the outlet and the basin divide (high point of the watershed length path) divided by the watershed length. Slope significantly affects flood magnitude as it is directly related to momentum of runoff.

c. Curve number is an empirical parameter derived as a function of land cover, soil characteristics (hydrologic soil group), and antecedent soil moisture conditions. There are various methods to derive a representative curve number for an area. This includes estimating the curve number based on the dominant land cover type. If multiple land covers exist within the area, find the area of each land classification within the basin and weight the curve number. Numerous tables have been established with common curve number values.

d. Routing parameters.

i. Time of concentration is the travel time for a particle of water from the furthest point of the watershed to the design point (outlet). Appendix B provides more details.

ii. Manning's n is an empirical coefficient for open channel flow, which generally represents friction forces on streamflow. It is based mainly on surface roughness.

iii. Channel geometry.

- Friction slope, or energy slope, is an estimation of the slope for the entire channel and plays an important role in hydraulics.

- Bottom width is an estimation of the average bottom width of the channel.

- Side slope is an estimation of the average side slope of the channel (Horizontal:Vertical) dimensions.

- Use hydrologic model predictions to guide assessments, treatments, and mitigation decisions.

- Design in situ postfire observations (appendix D).

Appendix B—Hydrologic Model Set Up and Descriptions

There is a wide selection of hydrologic models available for peak flow and hydrograph prediction. For rapid postfire hydrologic prediction numerous factors influence model selection. A decision tree can be used to provide guidance for hydrologic model section (figure B-1). Indepth model descriptions are provided below.

RCS

The 1949 “Probable Peak Discharges and Erosion Rates from Southern California Watersheds as Influenced Fire” by Rowe, Countryman, and Storey present a uniform method to estimate “normal” and postfire peak discharge and erosion for basins within national forests of southern California. This method establishes reasonable estimates of the average frequency and size of peak flow events and erosion rates associated with normal (unburned conditions), the effect of burned vegetation, and recovery of vegetation and hydrology with respect to time. Hundreds of look-up tables are provided for peak discharge and erosion rates from southern California watersheds (Rowe et al. 1949). Rarely, do basins burn completely. This model provides a method to determine the effects of partial burn on peak discharge and are summarized below.

- ❑ Compute the percent of area burned.
- ❑ Determine the average increase in peak discharge ratio for the percent of burnable area burned.

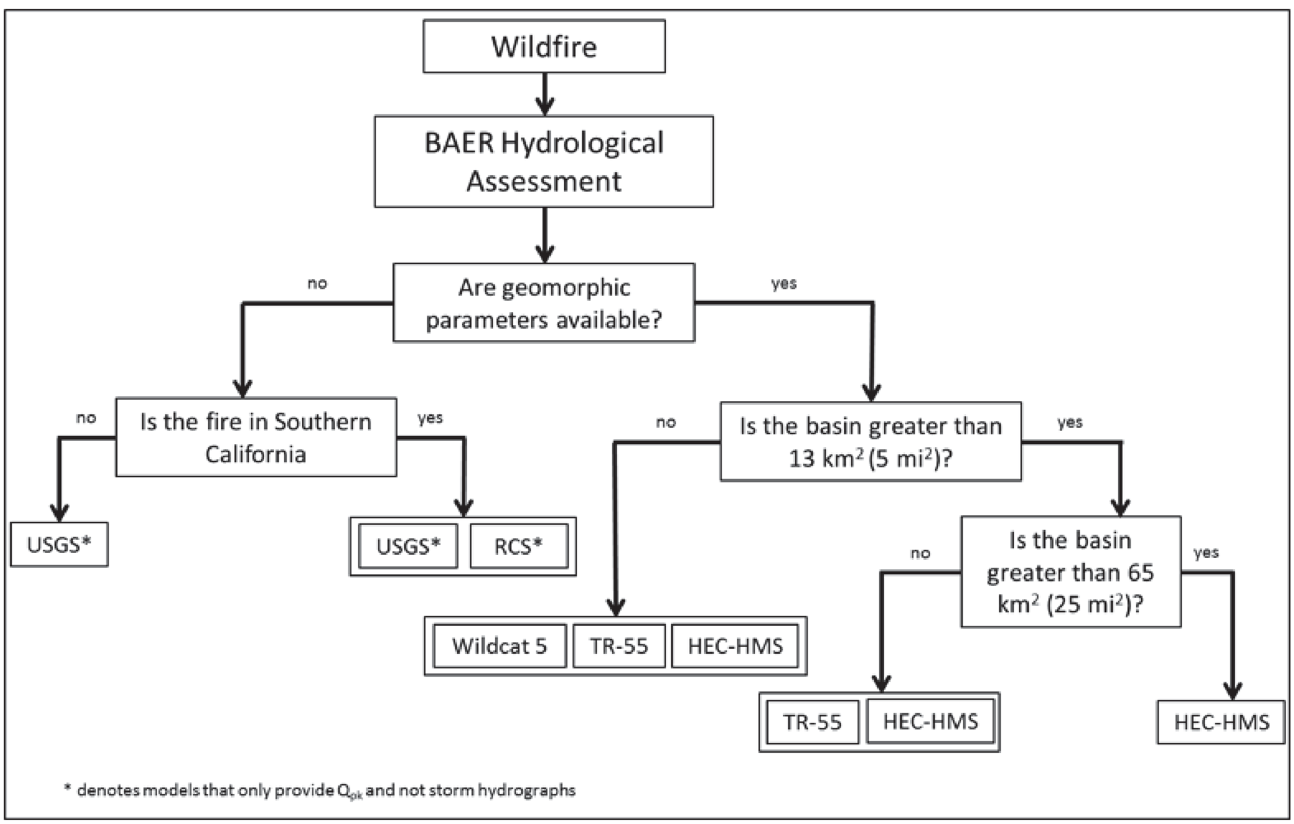

Figure B-1—Decision tree to provide guidance for model selection.

- ❑ Subtract the normal peak discharge of the frequency class from the tabulated peak discharge for the desired peak discharge year, resulting in the peak discharge of a complete burn.
- ❑ Multiply the increase in peak discharge for the complete burn by the increase in peak discharge ratio, resulting in the peak discharge from a partial burn.
- ❑ Add the increase in peak discharge resulting from the partial burn to the normal peak discharge to get the total peak discharge following the partial burn.

USGS Linear Regression

The U.S. Department of the Interior Geological Survey has published methods for estimating 2-, 5-, 10-, 25-, 50-, and 100-year peak discharge for ungauged sites for every State, the Commonwealth of Puerto Rico, and some metropolitan areas in the U.S. The regression equations are based on the National Flood Frequency program <http://water.usgs.gov/software/NFF/>, which has estimates of the magnitude and frequency of flood-peak discharges and flood hydrographs. Acquire and use these equations to estimate peak discharge. The regression equations used to estimate streamflow statistics for ungauged sites were developed through a regionalization process, involving regression analysis to relate streamflow statistics computed for a group of stream-gauging stations (typically within a State) to basin characteristics measured for the stations. These equations are transferred to ungauged sites with known basin characteristics. Users should be aware that estimates assume natural flow conditions.

A new product from the USGS and Environmental Systems Research Institute, Inc. (ESRI) is an interactive geographic information systems-based tool that integrates their regional equations to estimate design storms for ungauged or gauged basins. StreamStats is a Web-based model <http://water.usgs.gov/osw/streamstats/index.html> that allows users to delineate any basin of interest and generate peak discharge estimates. The following guidelines can be used to estimate peak discharge using StreamStats:

- ❑ On the StreamStats Web site, click “State Applications.”
- ❑ Choose a State by using the dropdown menu or clicking on the interactive map (figure B-2). The site will redirect you to a page with relevant information regarding the governing regression equations for the State.

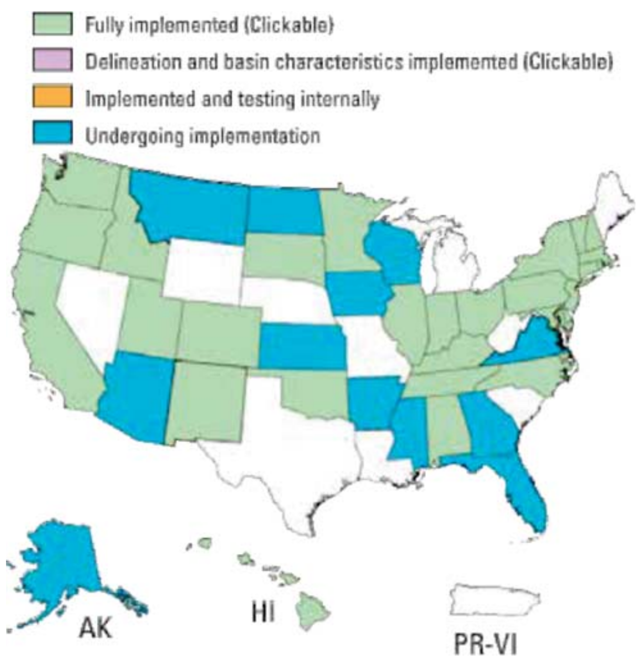

Figure B-2—U.S. Department of the Interior Geological Survey StreamStats interactive map of available State application (Web site accessed: April 2013).

- ❑ Zoom into the region of interest (at least 1:24,000 resolution).
- ❑ Select the “Watershed Delineation from a Point” tool and click on the outlet or design point of interest. StreamStats will delineate the basin of interest (figure B-3).
- ❑ Click on the “Estimate Flows using Regression Equations” tool. This will automatically generate a StreamStats site report with relevant information, such as location, latitude, longitude, land cover, and peak discharge (figure B-4).
- ❑ Click on the “Basin Characteristics” to compute a basin characteristics report with defined parameters.

Wildcat 5

Wildcat 5 is a Microsoft Excel program that is available from the University of Arizona. Wildcat 5 is suitable for watershed areas less than 5 square miles (mi^2) and time of concentration greater than 5 minutes. If the watershed is over 5 mi^2, Wildcat 5 significantly overpredicts peak runoff. If the time of concentration is less than 5 minutes, Wildcat 5 will generate an error message. The following sections overview the major concepts of Wildcat 5 and model setup:

- ❑ Model parameters.
- ❑ Model setup.
- ❑ Storm and storm distribution.

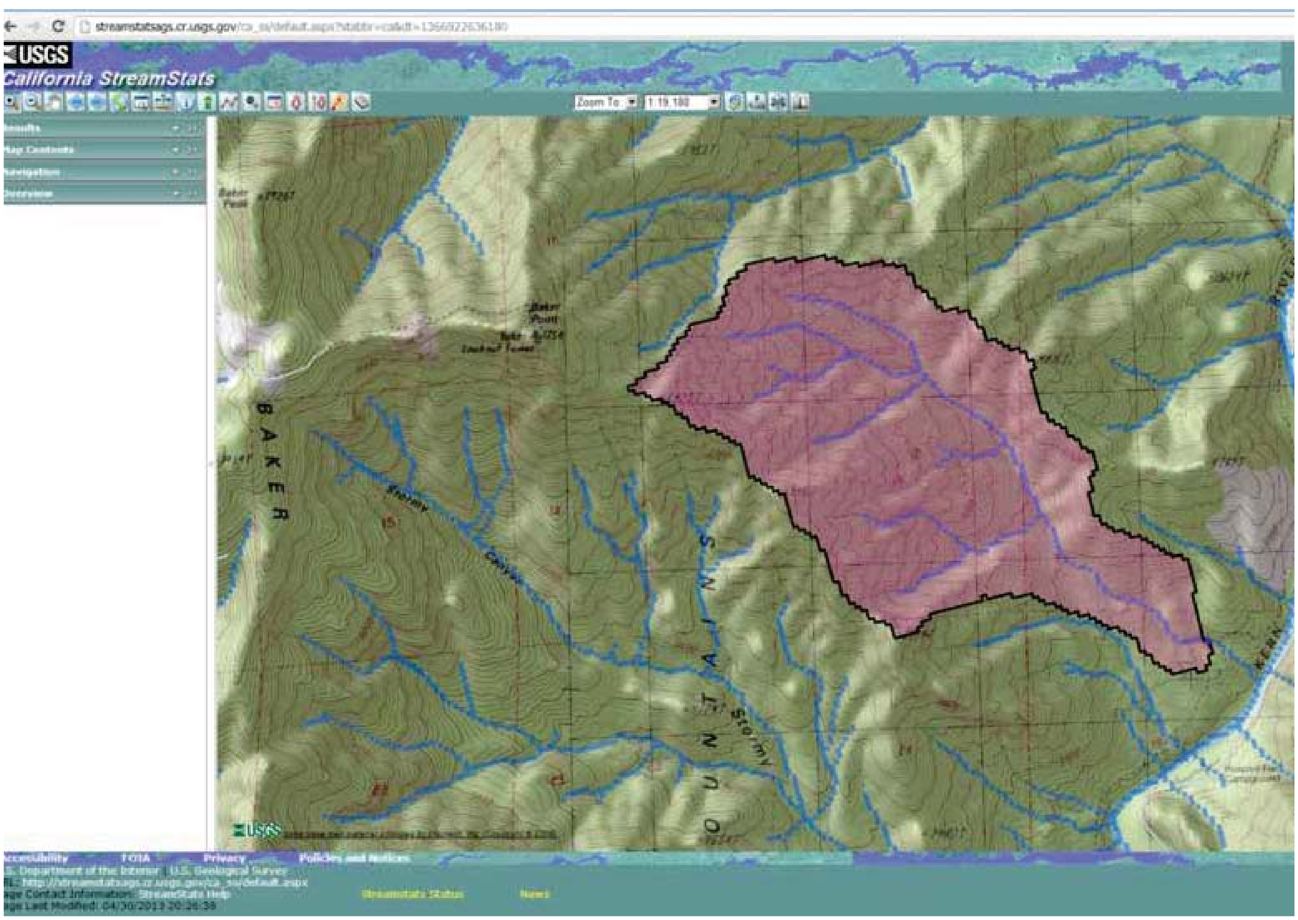

Figure B-3—USGS StreamStats application of “Watershed Delineation from a Point” tool (Web site accessed: April 2013).

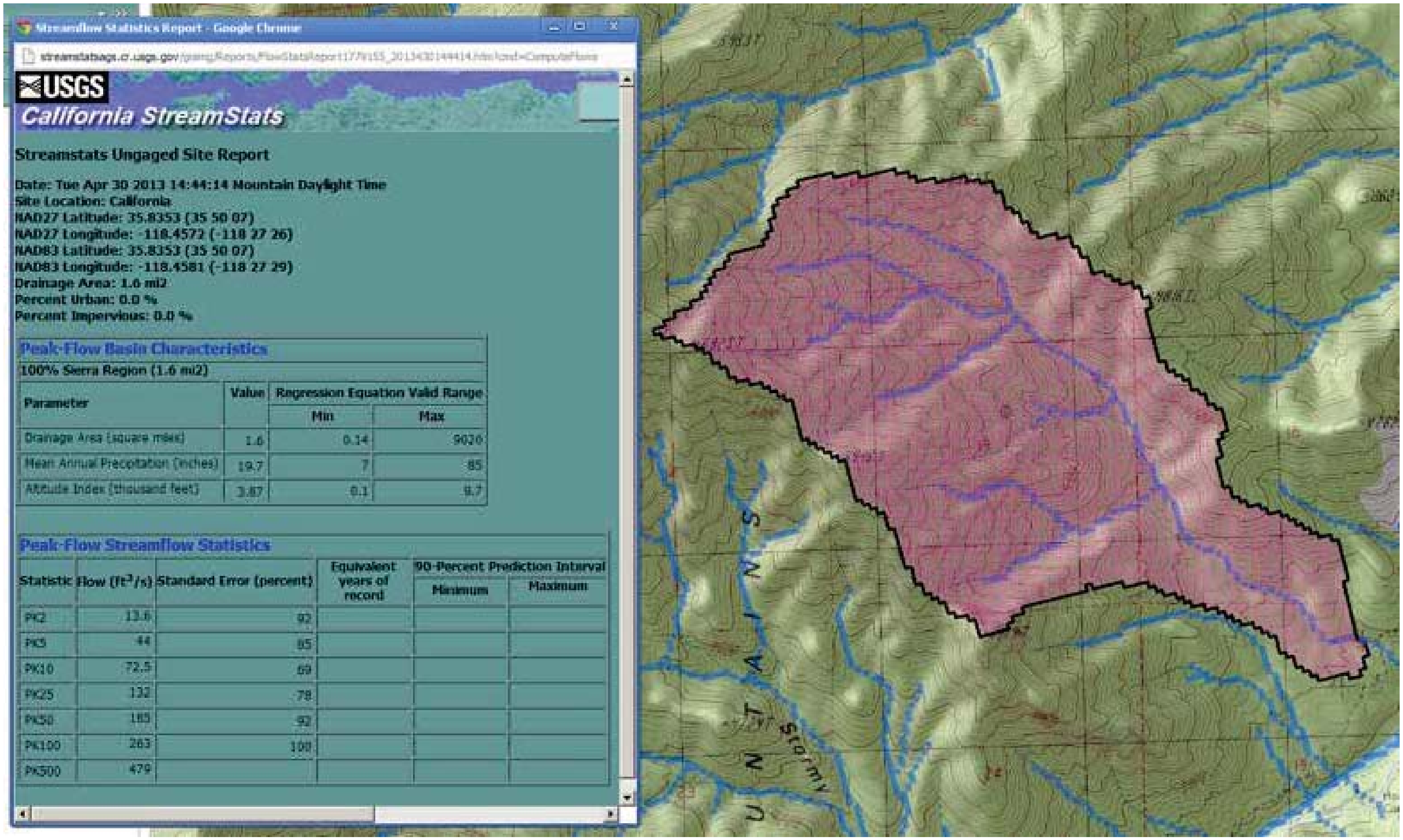

Figure B-4—USGS StreamStats Site Report (Web site accessed: April 2013).

- ❑ Rainfall excess options.
- ❑ Time of concentration.
- ❑ Unit hydrograph.
- ❑ Model simulation.

Model parameters
The model requires parameters that characterize the watershed; these include watershed area, length, channel slope, curve number, rainfall distribution, hydrograph type. The model output values include time of concentration, peak flow, peak time, total runoff depth, and runoff hydrographs.

Model setup
On the main screen enter relevant project identification data (figure B-5).

- ❑ Analyst.
- ❑ Project.
- ❑ Units systems (input and output).

Storm and storm distribution
On the main screen, select the orange "Storm and Storm Distribution" button and enter the appropriate information (figure B-6).

- ❑ Storm identification (i.e., Bull Fire #3 Type IA).
- ❑ Storm duration (i.e., 24 hours).
- ❑ Storm rainfall (i.e., 2.67 inches).
- ❑ Storm distribution (choose from three predesigned or create a custom distribution).
- ❑ Click "Accept & Continue."

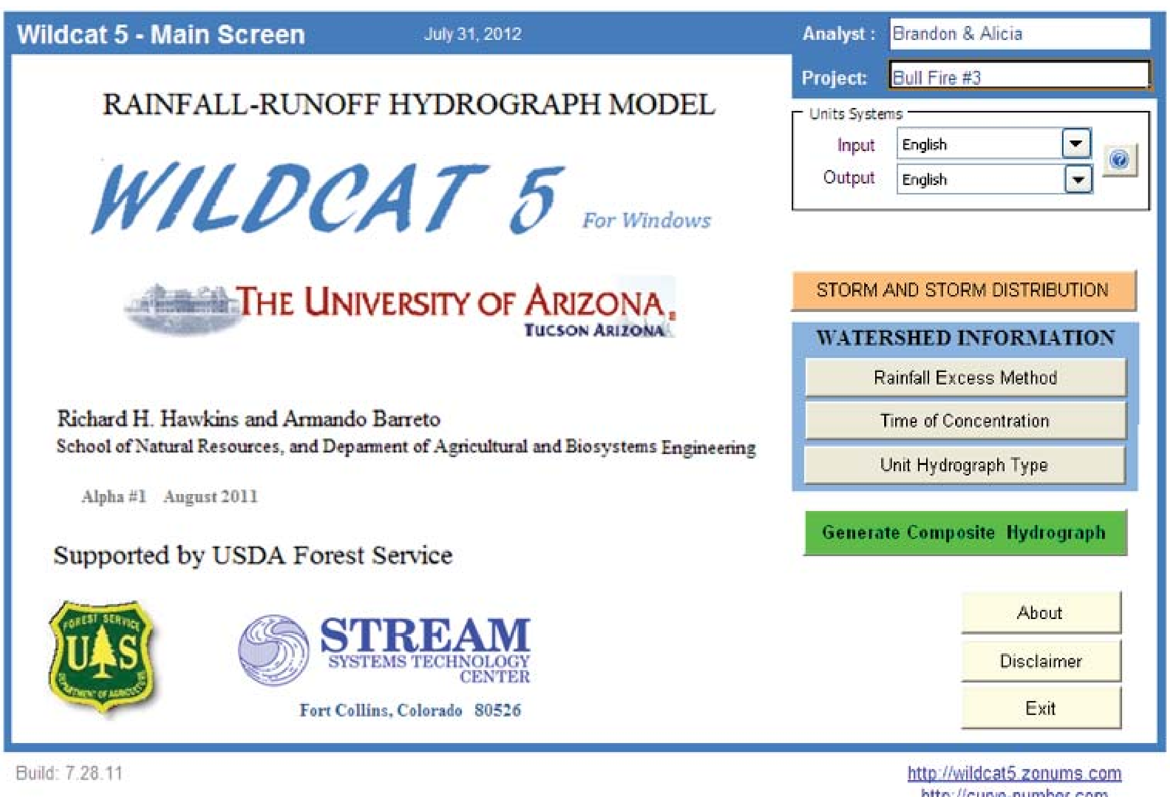

Figure B-5—Wildcat 5 main screen.

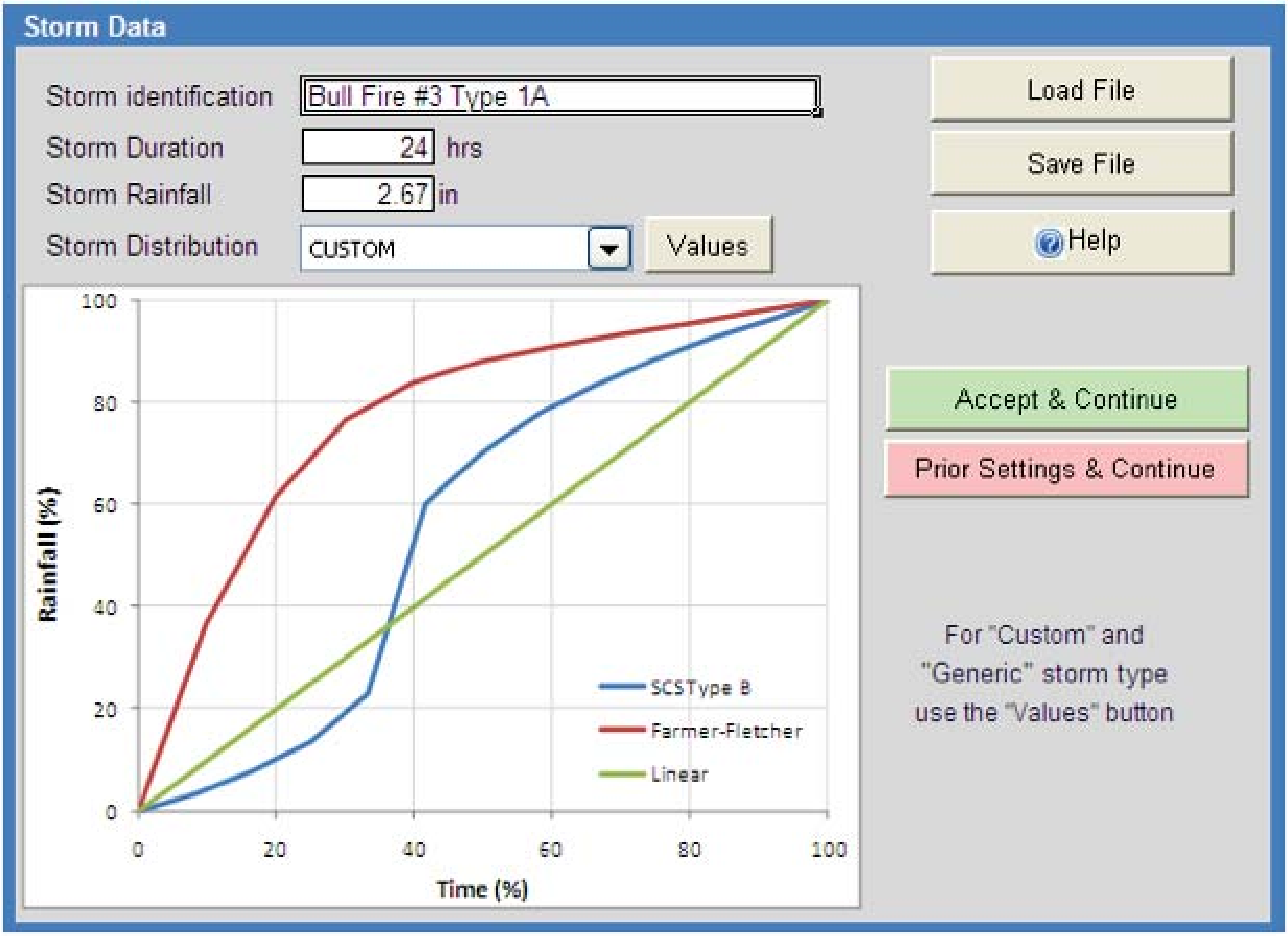

Figure B-6—Wildcat 5 "Storm and Storm Distribution" and options.

Rainfall excess options

On the main screen, select "Rainfall Excess Options" (figure B-7).

- ❑ Select a method and fill in the appropriate information
- ❑ Input the curve number value
- ❑ Click "Accept & Continue."

Time of concentration

On the main screen, select "Time of Concentration" (figure B-8).

- ❑ Enter Watershed Identification.
- ❑ In the "Time of Concentration/Lag Time" section choose a method for determining the time of concentration (i.e., calculate the time of concentration using Kent's equation, which uses land slope, channel length, curve number, and watershed area).
- ❑ Click "Accept & Continue."

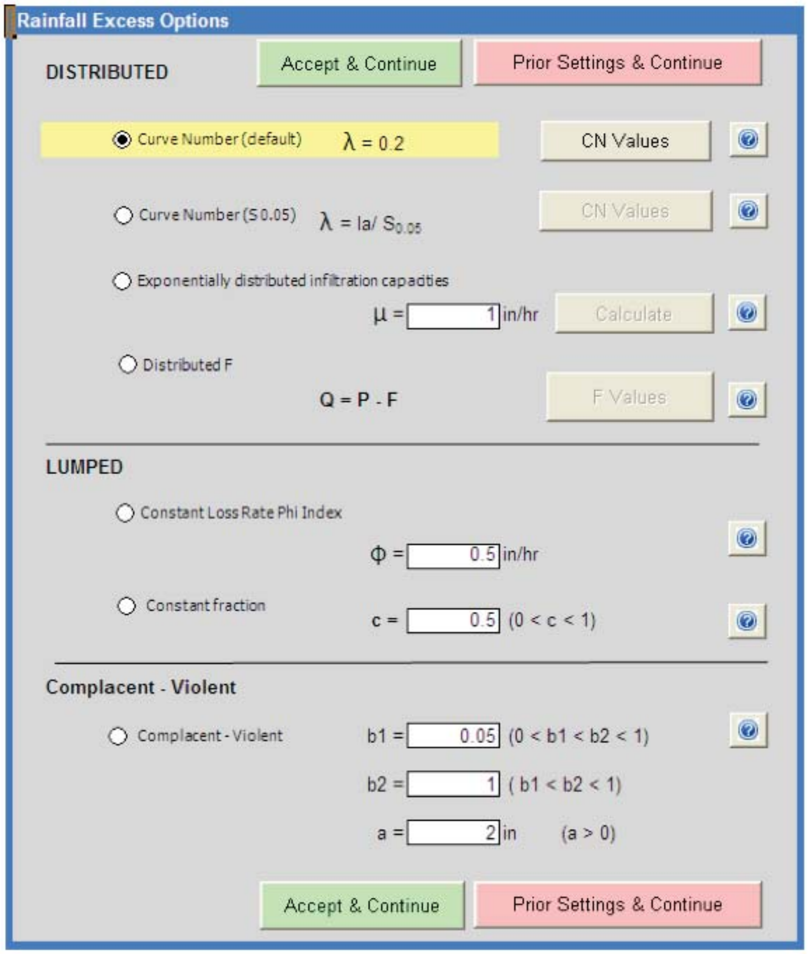

Figure B-7—Wildcat 5 "Rainfall Excess Options."

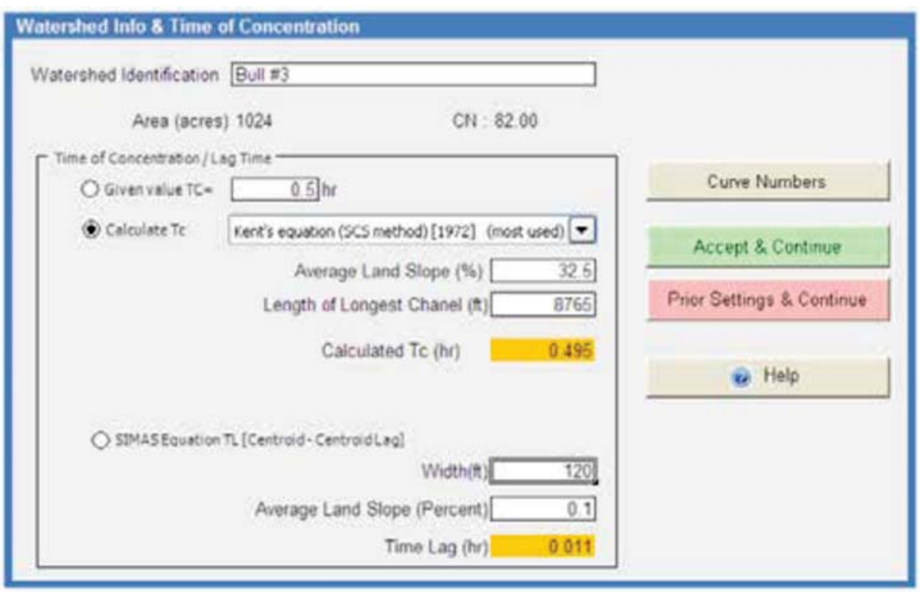

Figure B-8—Wildcat 5 "Watershed Info and Time of Concentration."

Unit hydrograph

On the main screen, select "Unit Hydrograph". Wildcat 5 has four options for unit hydrographs: Simple Triangular Unit Hydrograph, Variable Triangular Unit Hydrograph, Broken Triangular, and SCS Dimensionless Curvilinear (figure B-9).

- ❑ Select a predefined unit hydrograph (i.e., SCS Dimensionless Curvilinear).
- ❑ Click "Accept & Continue."

Model simulation

On the main screen, select "Generate Composite Hydrograph." Check the information in the "Summary Input Data" window for your model. If the information is correct, select "Calculate Hydrograph" to compute results (figure B-10). The model will generate several output options (figure B-11).

TR-55

The TR-55 program is freely available <http://www.wsi.nrcs.usda.gov/products/W2Q/H&H/tools_models/wintr55.html>. The following sections overview the major concepts of TR-55 and model setup:

- ❑ Model parameters.
- ❑ Model setup.
- ❑ Land use details.
- ❑ Storm data.
- ❑ Time of concentration.
- ❑ Reach data.
- ❑ Model simulation.

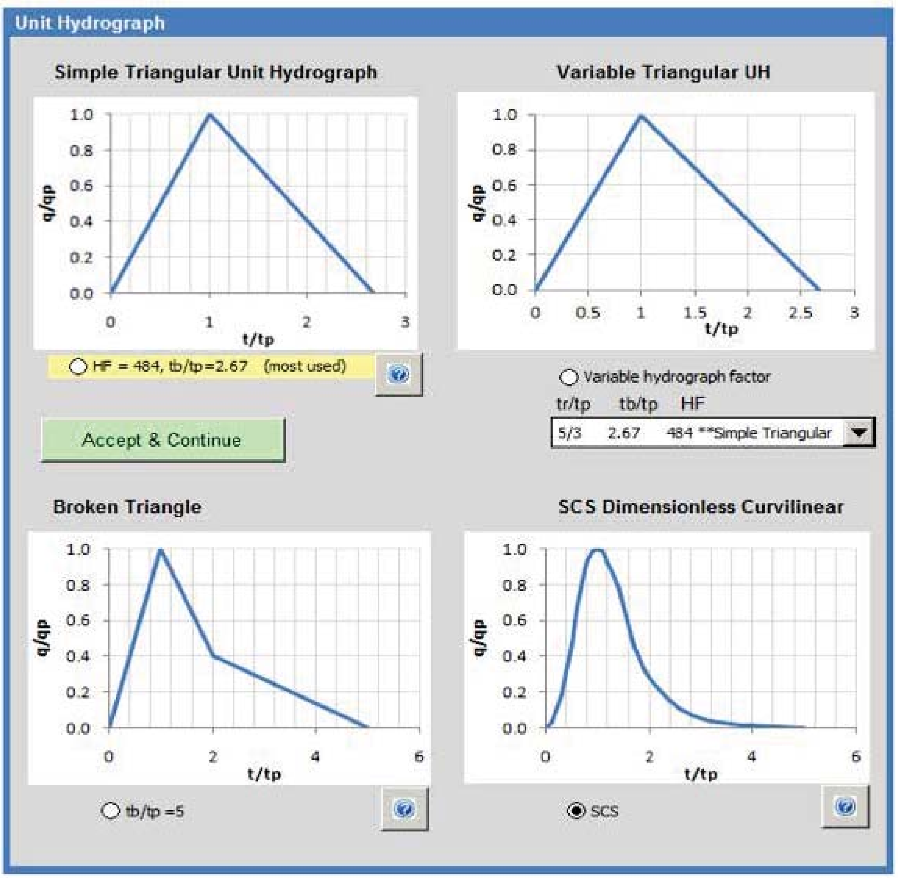

Figure B-9—Wildcat 5 "Unit Hydrograph."

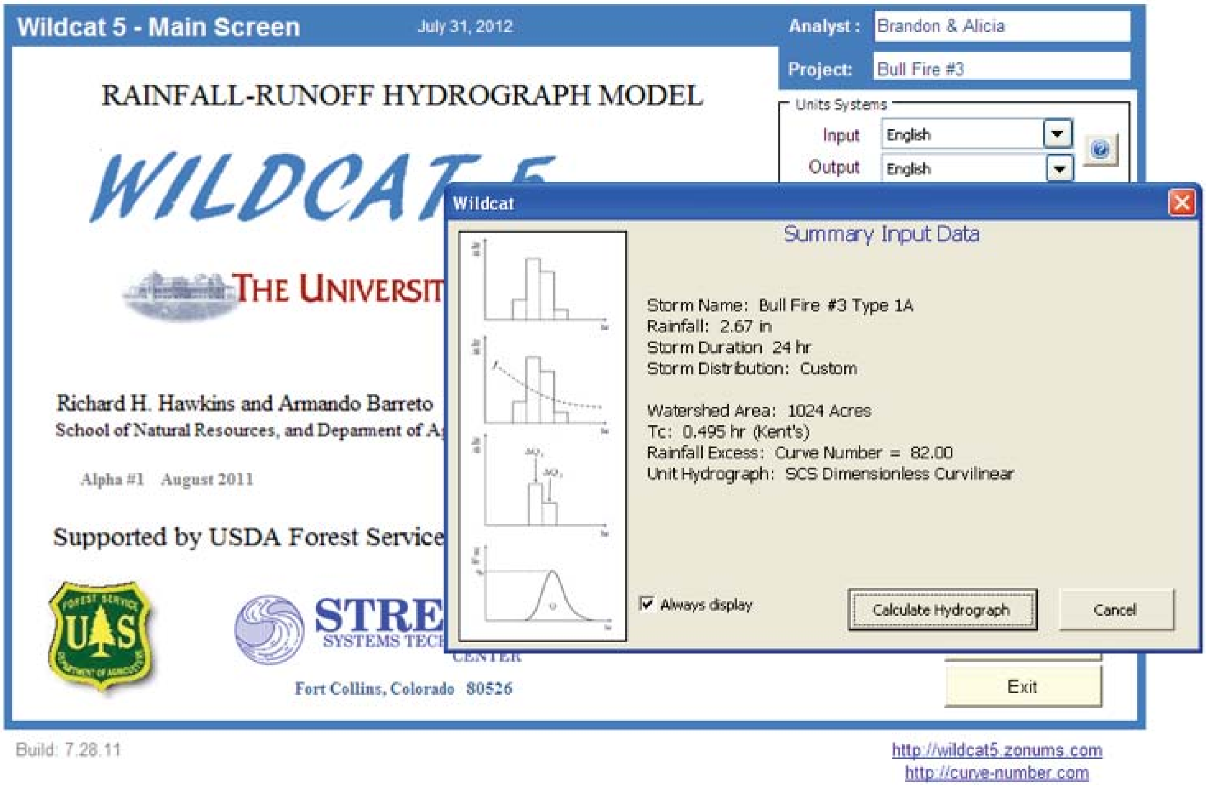

Figure B-10—Wildcat 5 "Summary Input Data."

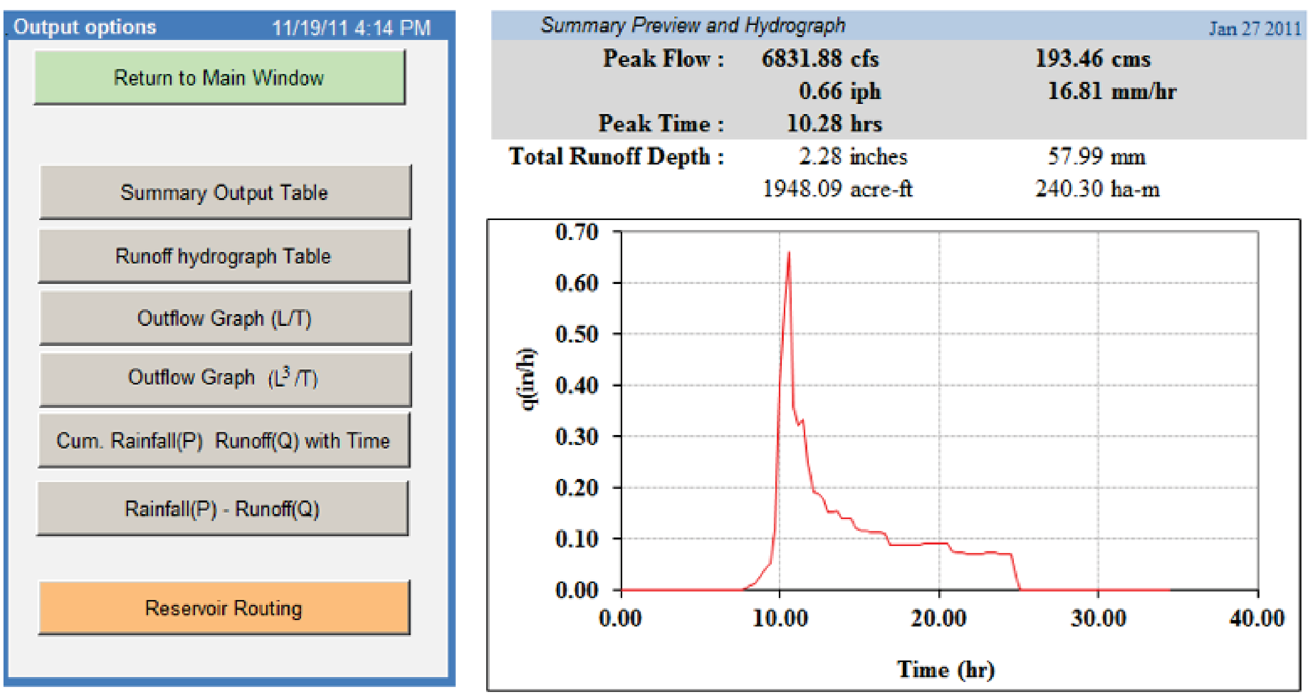

Figure B-11—Wildcat 5 "Output options" and "Summary Preview and Hydrograph."

Model parameters

The model requires parameters that characterize the watershed; these include watershed area, soil group, curve number, percent impervious, rainfall distribution type, and routing parameters. The model output values include peak flow, peak time, total runoff depth, and runoff hydrographs.

Model setup

Find “Engineering Applications” in the computer Start menu and open the TR-55 model by selecting “Start.” On the main screen enter relevant project identification data (figure B-12).

Figure B-12—TR-55 Main Window.

- ❑ User.
- ❑ Project.
- ❑ State.
- ❑ County.

In the “Options” menu, select the units for the model (i.e., English) and in the main menu choose the appropriate units for “Sub-areas are expressed in:” Under “Dimensionless Unit Hydrograph,” select “standard.”

Land use details

In the “ProjectData” menu, select “Land Use Details” (figure B-13), repeat this step as necessary.

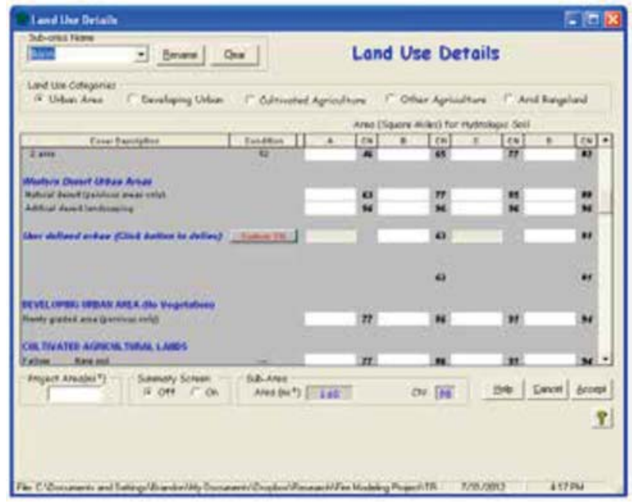

Figure B-13—TR-55 “Land Use Details.”

- ❑ Create a “Sub-area Name” at the top and “enter.”
- ❑ Scroll down to “User defined urban” and click on “Custom Curve Number” (figure B-14).

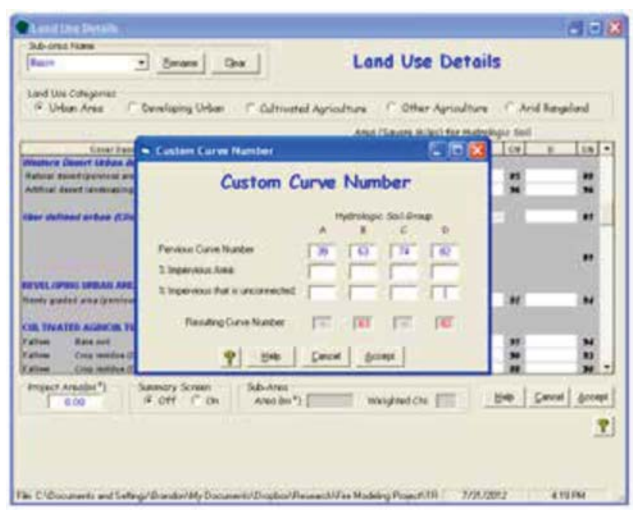

Figure B-14—TR-55 “Custom Curve Number.”

- ❑ Input relevant curve number, soil group type, and percent impervious.

❑ Click “Accept.”

❑ Enter the area (lumped area or subbasin area) next to the newly created custom CN.

❑ Click “Accept.”

Storm data

In the “GlobalData” menu, select “Storm Data” (figure B-15).

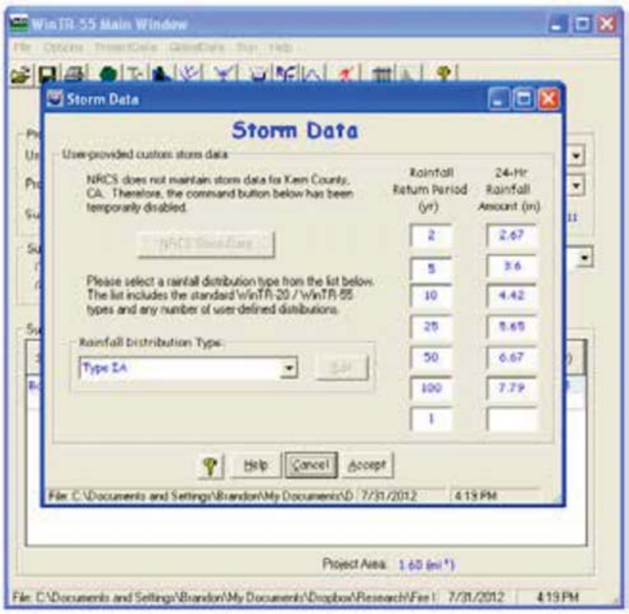

Figure B-15—TR-55 “Storm Data.”

❑ Enter the NOAA Precipitation Frequency Estimates for the 2-, 5-, 10-, 25-, 50-, and 100-year storm precipitation return intervals at “24-hours” in Storm Data.

❑ Enter the Rainfall Distribution Type in the designated box.

❑ Click “Accept.”

Time of concentration

Calculate the time of concentration in hours and manually enter this value (circled in red in figure B-16).

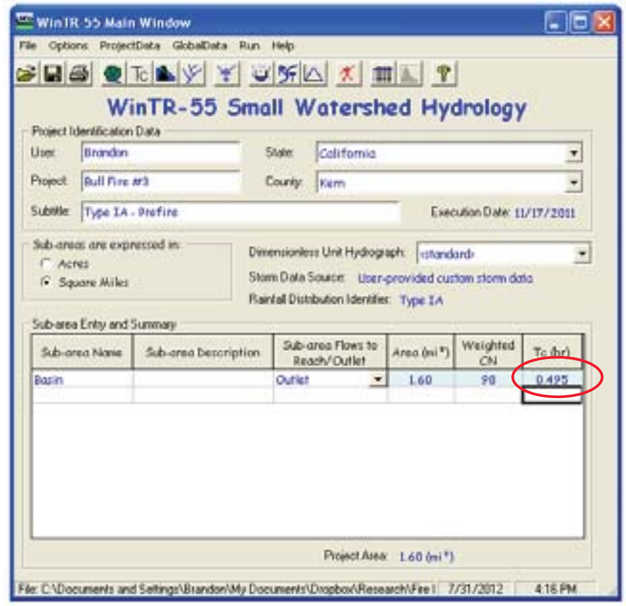

Figure B-16—TR-55 manual entry of time of concentration highlighted with a red circle.

Reach data

Reach data is necessary in a distributed model. In the “ProjectData” menu, select “Reach Data.”

❑ Enter all relevant geomorphic parameters.

❑ Friction slope is the channel slope (V:H).

❑ Side slope is the slope of the channel’s banks (V:H).

❑ If you encounter an error “A reach has not been provided for subarea:” click “OK,” this will be resolved in the following steps.

❑ Set the correct flow path for routing flow in distributed basins by selecting the dropdown menu for each subbasin in the “Sub-area flows to Reach/Outlet.”

❑ Check that the flow path is correct under the “ProjectData” menu in “Reach Flow Path.”

Model simulation

In the “Run” menu, select all applicable return periods and click Run (figure B-17). The model will generate a summary of the peak flows (figure B-18). On the main screen, selecting the hydrograph button will provide the option to “Output Graphics” (view hydrographs) by subareas, outlets, reaches, and storms (figure B-19). Select “Plot” to display the hydrographs.

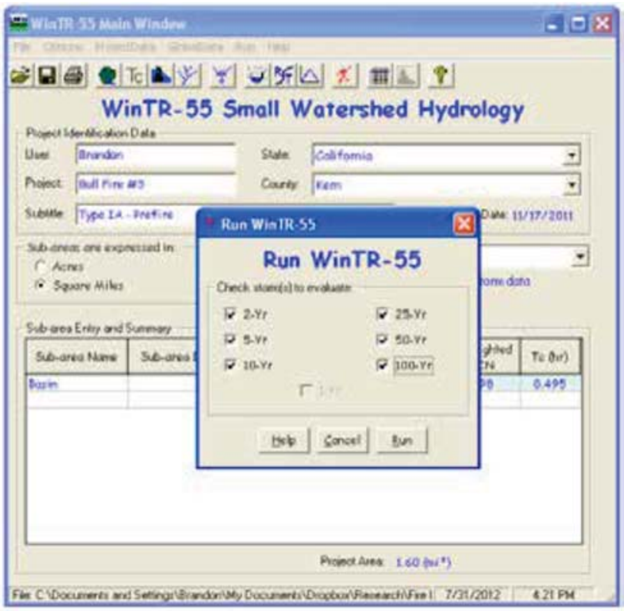

Figure B-17—TR-55 “Run.”

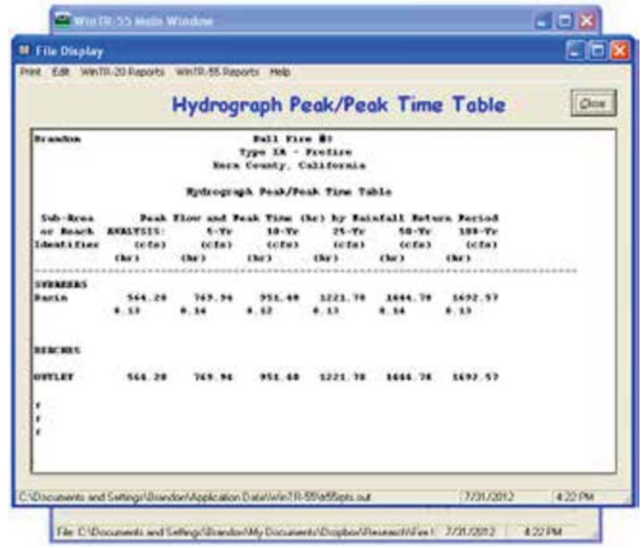

Figure B-18—TR-55 summary of peak discharge.

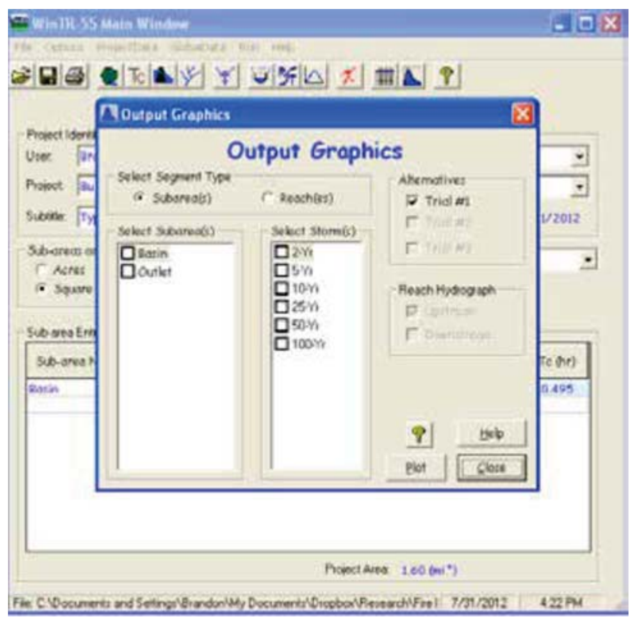

Figure B-19—TR-55 “Output Graphics.”

HEC-HMS

To develop a model in HEC-HMS requires several steps. The following sections overview the main concepts of HEC-HMS and model setup:

- ❑ Model set up.
- ❑ Basin model manager.
- ❑ Subbasin parameters.
- ❑ Open channel routing.
- ❑ Meteorological data (design storms).
- ❑ Time series data.
- ❑ Model simulation.

Model set up

Open the HEC-HMS model. In “File,” select “New” and provide the appropriate information for Name, Description, and Location (figure B-20). Use the dropdown menu to define the unit system.

Basin model manager

In “Components,” select “Basin Model Manager.” The physical representation of the watershed or basin is configured in the basin model and hydrologic elements are connected in a dendritic network to simulate runoff processes. The available elements are: subbasin, reach, junction, reservoir, diversion, source, and sink. Computation proceeds from upstream elements in a downstream direction. Junctions are where streams/subbasins meet and reaches connect junctions and are used to route flow downstream.

- ❑ Create a “New” basin model, which will be in a subfolder under the project (figure B-21).
- ❑ Provide a name and description for the basin and select “Create.”
- ❑ Double click (or hit the + button to the left of the folder) on your Basin Model Folder to see the Model. Double click on the Model or watershed/basin symbol. This should open a blank or gridded screen (working area) with various tools located across the top tool bar, which you use to design the watershed.
- ❑ Create subbasins, junctions, and reaches to route flow through the system. Click the appropriate icon—move the mouse to the blank work area and click again. An icon will appear. Click on the arrow in the icon/graphical user interface area to activate the mouse again (figure B-22). General guidelines: each subbasin outlet is a junction. If there is flow from a subbasin tributary into a main channel, there should be a junction. The design point/outlet also is a junction. Use reaches to connect all junctions. Connect each subbasin to a junction, junctions to a reach, and reaches to the outlet. Make connections by left clicking on the component (i.e., subbasin) and designating where you want the downstream connection (i.e., junction). Right click on the downstream component to connect. Continue until you connect all components. Check that you have connected the components correctly or the model will have errors.

Figure B-20—HEC-HMS “Create a New Project.”

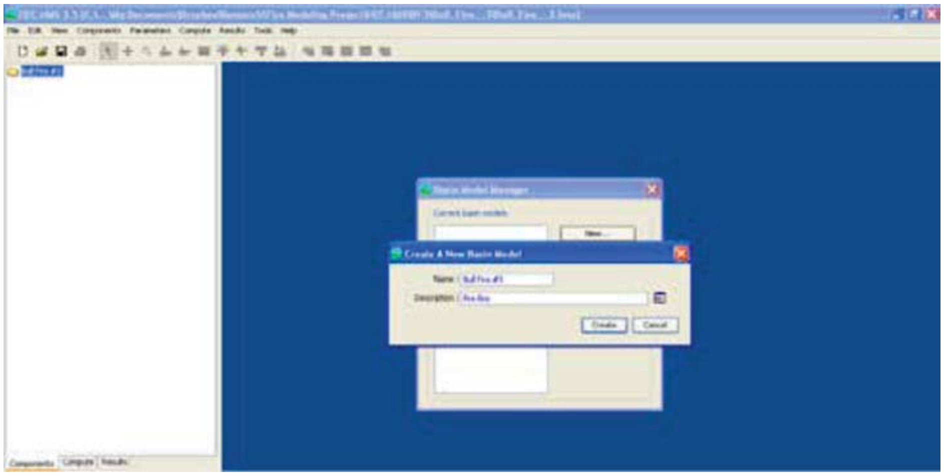

Figure B-21—HEC-HMS “Create a New Basin Model.”

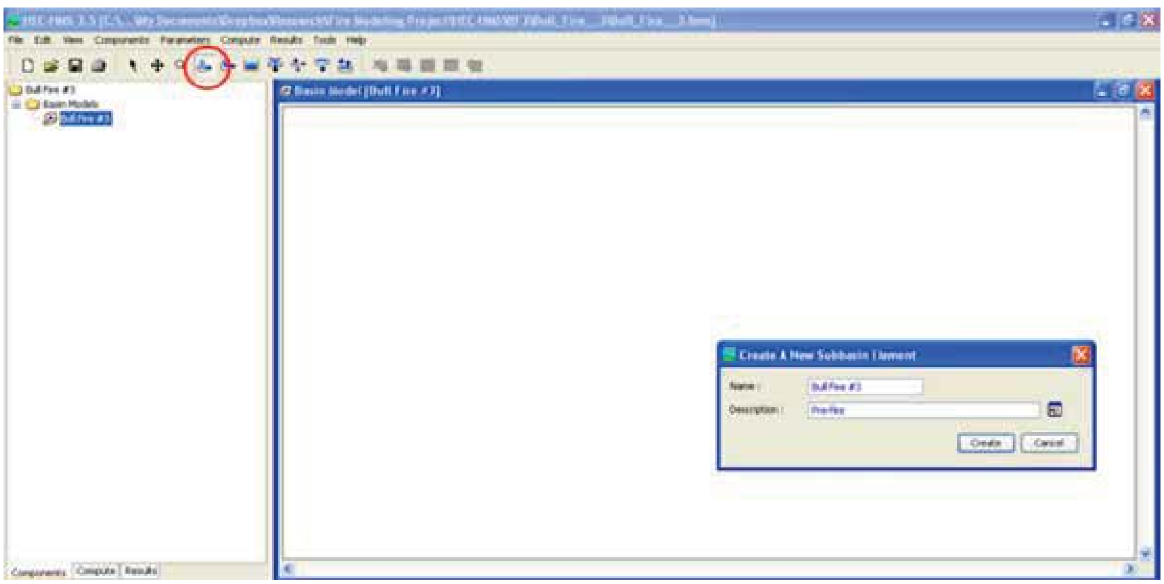

Figure B-22—HEC-HMS “Create a New Subbasin Element” tool highlighted with a red circle.

Subbasin and routing parameters

Each subbasin requires a defined method for each parameter (Loss Rate, Transform, and Baseflow). In the Subbasin tab, provide a description for the subbasin and area. Define the method that you will use with the dropdown menus (i.e., Loss Rate: SCS Curve Number; Transform: U.S. Department of Agriculture, Soil Conservation Service (SCS) Unit Hydrograph; Baseflow: Constant Monthly) (figure B-23). Click on each parameter tab to input the required information. A summary of the options for each parameter are as follows:

- ❑ Define the Loss parameters for each subbasin. Various methods are available to simulate infiltration losses (to account for losses from precipitation). These methods apply only to pervious surfaces. Options for event simulations (single rainfall-runoff storm) include: deficit and constant, Green and Ampt, gridded SCS curve number, gridded soil moisture accounting, initial and constant, SCS curve number, and soil moisture accounting.
- ❑ Define the Transformation parameters for each subbasin. The excess precipitation (from the loss model) will be transformed into surface runoff. The various methods available within HEC-HMS include: Clark unit hydrograph, Synder unit hydrograph, SCS unit hydrograph, user-specified unit hydrograph, kinematic wave model, and ModClark.
- ❑ Define the Baseflow for each subbasin. Ephemeral streams or intermittent streams have periodic flow during the water year. Perennial streams have continuous flow all year (not just during or immediately after rainfall). Account for baseflow when simulating storm flows in systems with contributing baseflow. Estimate values from local streams and conditions of similar scale and size.

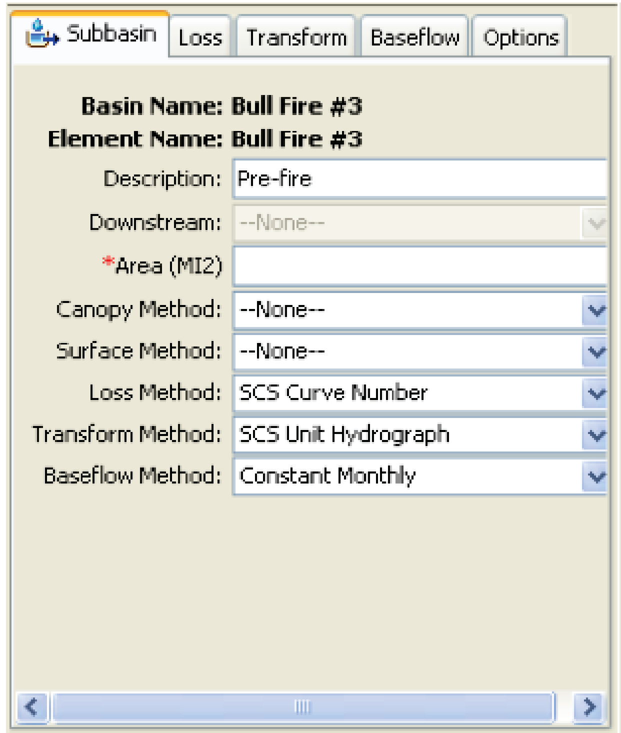

Figure B-23—HEC-HMS subbasin methods

Open channel routing

Each Reach requires a defined method. There are a variety of open channel routing methods available for simulating flow in distributed basins with open channels (or reaches). They are: kinematic wave, lag, modified Puls, Muskingum, Muskingum-Cunge 8-point section, and Muskingum-Cunge standard section.

Meteorological data (design storms)

Assign the precipitation value for each storm to each subbasin within the watershed model.

- ❑ In “Components” → “Meteorological Model Manager” → “New.”
- ❑ Name each Met Model with the Storm names (i.e., Met 1=2-year, Met 2=5-year, etc.)
- ❑ The Met Model will be linked under the Met Model on the left. Click on the storms to modify the data.

- ❑ Select “Specified Hydrograph” to input customized precipitation data, otherwise select “SCS Storm.”
- ❑ In the “Basins” tab select “Yes” on “Include Subbasins.”
- ❑ In “Precipitation,” select a rainfall distribution type (i.e., Type 1A rainfall distribution) and enter a depth (i.e., 2.67 for a 2-year 24-hour storm).

Time series data

- ❑ Time series data (i.e., precipitation) can be entered into the model. In “Components” → “Time-Series Data Manager” → “Select Precipitation Gauge” → “New.”
- ❑ Each gauge can be labeled as one storm.
- ❑ The gauge that is created will be linked on the left under Time-Series Data (description is under each gauge).
- ❑ Click on this the link for the gauge.
- ❑ “Start Date” will be the starting date of the storm.
- ❑ “End Data” will be the ending date of the storm.
- ❑ Define the time interval (in Time Series Gauge).
- ❑ Copy and paste data to the “Table.” View the data in the graph section. HEC-HMS leaves the first day blank (you cannot enter data for the first hour)—this is a warm up period for the model.
- ❑ Repeat this process for each storm. Include adequate time after the storm to simulate storm streamflow recession.

Model simulation

Inputting the basin characteristics meteorological data for a design storm in HEC-HMS will output storm runoff hydrograph, runoff volume, and timing. If there are multiple subbasins, the model will estimate the flow from each contributing area and reaches, in addition to total flow. There also is an optimization feature to calibrate and improve the model. The HEC-HMS also offers the option to input observed streamflow to assist with model evaluation and calibration (similar to precipitation time series data).

- ❑ The model requires control specifications before you can execute it. Go to “Components” → “Control Specifications Manager” → “New” and name the control specification (i.e., 2-year Design Storm). Enter start and stop dates and a run description for the event. Note: if using time series data, be sure to run the model an extra 5-10 days after the storm dates to assure simulation of the entire hydrograph.
- ❑ In “Compute” → “Create Simulation Run” → Name the simulation run (i.e., 2-year, 5-year, etc.). Select the Basin Model, the appropriate Met Model (i.e., 2-year, 5-year, etc.), and the control specification.
- ❑ In “Compute” → “Select Run” select a simulation to run (figure B-24).
- ❑ Use “Compute Run” to execute the model.
- ❑ If observational data is available to compare the model simulations to the observed discharge, click on the outlet (under the basin model) and select “Options” → “Observed Flow.” Add the storm name to compare the observed flow.

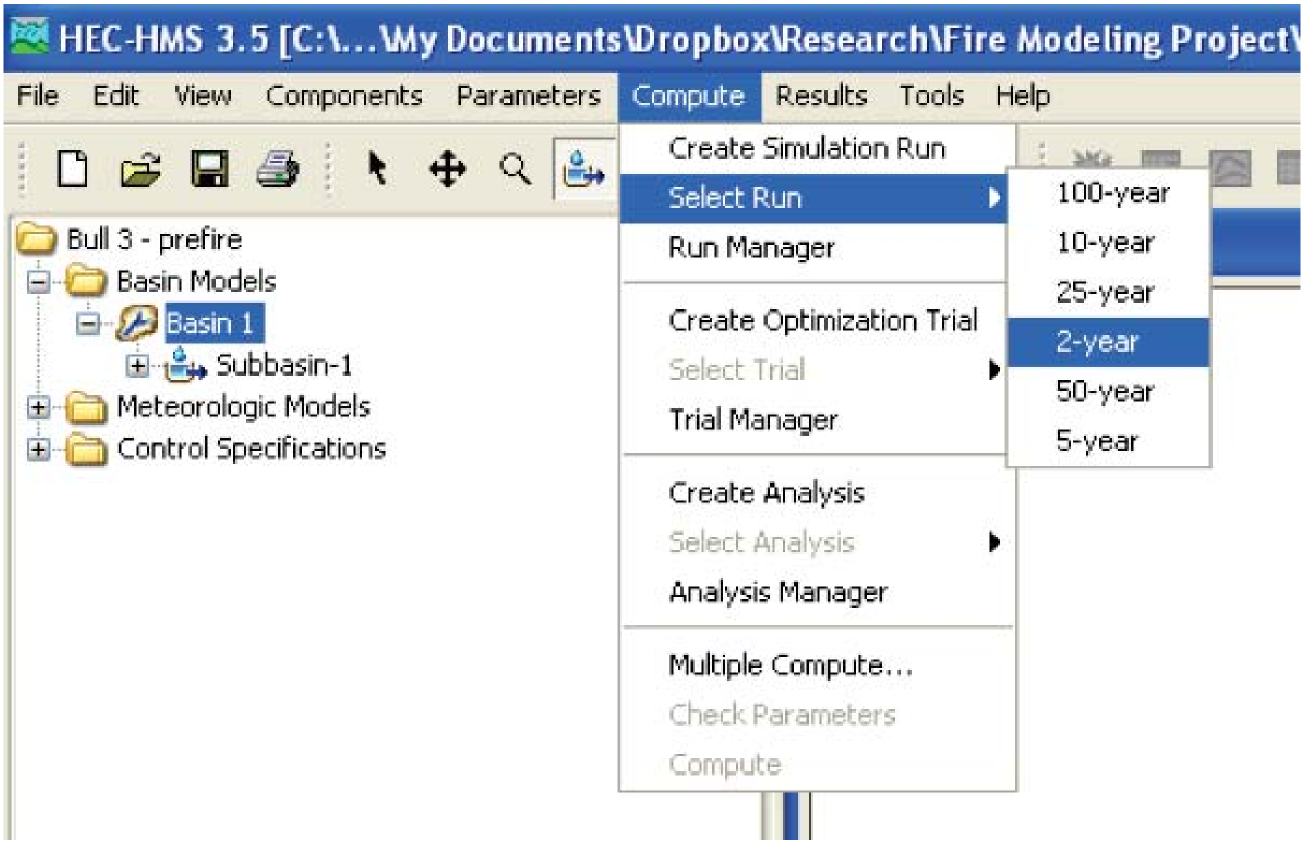

Figure B-24—HEC-HMS "Select Run."

The model should run. If there are warnings, the model still ran. Typically, the warnings are associated with the time of concentration or lag time (if the computed time of concentration is less than the model time interval or the initial abstractions are unrealistic). If there are errors, the model did not run. To view results, right click on the outlet junction → "view results" → select "Graph", "Summary", or "Time series Table" (figure B-25).

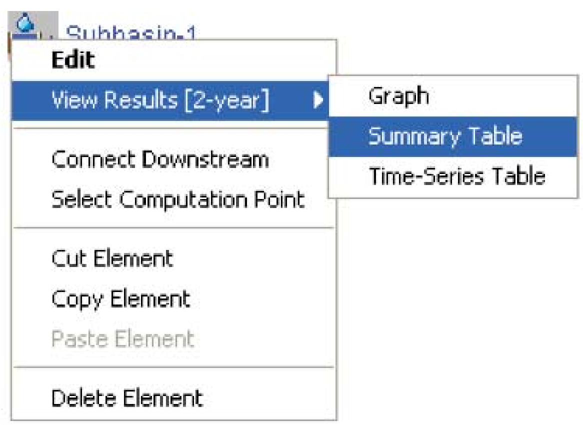

Figure B-25—HEC-HMS "View Results" at the outlet.

Appendix C: Application of Models to the Bull Fire

A case study is outlined to provide training for a selection of models applied to a burned watershed in the Sequoia National Forest in California, including an overview of model parameter estimation, model simulations, output response, and postfire hydrologic assessment. Four prefire models use data from the case study: USGS Regression, Wildcat 5, TR-55, and HEC-HMS. Finally, you will alter these models to represent postfire conditions and to predict postfire runoff.

The city of Kernville, northeast of Bakersfield in Kern County, California, is in the southern Sierra Nevada. The Bull Fire burned 16,448 acres along the Kern River, north of Kernville in August 2010. The area burned consisted mainly of grass, chaparral, and timber (higher elevations). The dominant vegetation types consist primarily of annual grassland, California buckwheat scrub, and ceanothus mixed-chaparral. Scattered vegetation includes Gray Pine Savanna, Interior Live Oak, and Black Oak. Along the riparian areas, vegetation consists of mixed hardwood (i.e., white alder, willow, cottonwood, California sycamore). The Bull Fire burned 15,830 acres on the Sequoia national Forest and 618 acres of private land. The climate in the Kernville area is characterized by cool, wet winters and hot, dry summers. The area is affected by winter rain and snow, typically between November and April. Thunderstorms are a normal occurrence between July and September. Less frequently, the area is prone to rain-on-snow events, which may result in extensive flooding.

Based on the Hydrologic Unit Code 7 (HUC 7), watersheds affected by the Bull Fire are delineated. Areas of concern, within the Kern River basin are delineated based on pour points. Watershed selection for postfire monitoring is based on accessibility, soil burn severity, size, and fire history. The site chosen for model application is an unnamed watershed (9CN Unnamed), which will be referred to as Bull Fire #3. The Bull Fire #3 basin is east of the North Fork Kern River; according to the BAER report it is identified as having a high potential for flooding and increased sediment flow. This is due to the high percentage of high and moderate soil burn severity. Values at risk from flooding and sedimentation from burned basins west of the North Fork of the Kern include recreation sites (Headquarters, Camp 3, Hospital Flat, Corral Creek, Mountain Route 99, Arch Sites, Riverkern, Southern California Edison (SCE) Roads, Whitesides Cabin, fisheries, and the Kern River Golden Trout Resort).

1. Estimate geophysical parameters. Geophysical basin parameters for the Bull Fire are estimated using tools such as ArcGIS.

    a. Watershed area (A): 1.60 square miles (mi^2)

    b. Channel length (LC): 7,600 feet (ft)

    c. Watershed length (L): 8,800 ft

    d. Altitude Index (H): 3.87 (in thousands of feet)

       The average of two elevations, Ea and Eb. Ea, is the elevation at 0.1*L and Eb, is the elevation at 0.85*L.

    e. Watershed slope ($S=\Delta E/L$): 0.518

       ΔE is the difference in elevation of the basin divide (end point of watershed length) and the outlet (design point).

2. Estimate soil burn severity

   Using soil severity maps (RSAC), the soil burn severity for Bull Fire #3 is classified as: High: 3 percent, Moderate: 68 percent, Low: 13 percent, and Unburned severity: 16 percent.

3. Estimate climate parameters for each model

   a. USGS Regression—Mean Annual Precipitation (MAP) estimated from local weather stations or on site instrumentation. For the Bull Fire the MAP is estimated from the NOAA Kern River Power House #3: <http://www.wrh.noaa.gov/hnx/coop/pwrhse3.htm> and is 19.7 inches.

   b. Wildcat 5—Soil Conservation Service (SCS) storm distribution constructed for each recurrence interval using the NOAA Atlas 14, 24-hour depth of rainfall value for each recurrence interval.

   c. TR-55—NOAA Atlas 14, 24-hour rainfall for each recurrence interval.

   d. HEC-HMS—SCS Type I storm.

4. Estimate the Curve Number for CN models

   The dominant land-cover type for Bull Fire #3: Chaparral/scrub oak. For the Bull Fire 3 site, we referenced the Mays Water Resources Engineering book for typical chaparral/scrub oak CN values and the soil type was identified as D from an online U.S. Department of Agriculture Natural Resources Conservation Service Web Soil Survey <http://websoilsurvey.nrcs.usda.gov/app/HomePage.htm>, where an ArcGIS shapefile (maximum size of 10,000 acres) can be imported to obtain a detailed summary of soil types for the area of interest.

5. Estimate routing parameters (vary by model)

   a. Time of concentration (Tc): 0.495 hrs

   b. Manning's n

   c. Channel geometry (friction slope, bottom width, side slope)

6. Prefire Models

USGS Regression Model

Use StreamStats to determine prefire peak discharge or determine the equations used for the region of interest. StreamStats uses the California Sierra Region developed by Waananen and Crippen (1977):

$$Q_2 = 0.24A^{0.88}\ P^{1.58}\ H^{-0.80}$$

$$Q_5 = 1.20A^{0.82}\ P^{1.37}\ H^{-0.64}$$

$$Q_{10} = 2.63A^{0.80}\ P^{1.25}\ H^{-0.58}$$

$$Q_{25} = 6.55A^{0.79}\ P^{1.12}\ H^{-0.52}$$

$$Q_{50} = 10.4A^{0.78}\ P^{1.06}\ H^{-0.48}$$

$$Q_{100} = 15.74A^{0.77}\ P^{1.02}\ H^{-0.43}$$

where: A = watershed area (square miles)
P = mean annual precipitation (inches)

The Regression Equation Variables are A = 1.60 mi2, P = 19.7 in, and H = 3.87 (thousands of feet). The prefire peak discharge using StreamStats: see table C-1.

Table C-1—USGS Regression Equation Bull Fire #3 prefire peak discharge

Event	Q [cfs]
2-yr	14
5-yr	44
10-yr	73
25-yr	132
50-yr	185
100-yr	263

Wildcat 5

Utilizing the procedure from appendix B and the appropriate variables, the prefire peak flow using Wildcat 5: see table C-2.

Table C-2—Wildcat 5 Bull Fire #3 prefire peak discharge

Event	Q [cfs]
2-yr	167
5-yr	302
10-yr	431
25-yr	633
50-yr	805
100-yr	995

TR-55

Relevant model parameters for the TR-55 method: see table C-3.

Table C-3—TR-55 relevant model parameters

Area [mi^2]	1.60
Soil Group	D
CN	81
% impervious	0
Rainfall Distribution Type	Type IA
T_c [hrs]	0.511
Manning's n	N/A
Friction Slope	N/A
Bottom Width	N/A
Side Slope	N/A

Storm precipitation values: see table C-4.

Table C-4—TR-55 storm precipitation values

Event	NOAA Atlas rainfall [in]
2-yr	2.67
5-yr	3.60
10-yr	4.42
25-yr	5.65
50-yr	6.67
100-yr	7.79

Utilizing the procedure from appendix B and the appropriate variables, the prefire peak flow using TR-55 is: see table C-5.

Table C-5—TR-55 Bull Fire #3 prefire peak discharge

Event	TR-55 pre-fire Q [cfs]
2-yr	214
5-yr	392
10-yr	563
25-yr	833
50-yr	1064
100-yr	1319

HEC-HMS

Loss Rate (SCS curve number method) parameters, see table C-6.

Table C-6—HEC-HMS loss rate parameters

Total Area [mi²]	1.60
Initial Loss [in]	0.59
SCS Curve Number [dimensionless]	81
Total % Impervious	0

Transform Method (SCS Unit Hydrograph method) parameters, see table C-7.

Table C-7—HEC-HMS transform method parameters

Length [ft]	8,765
Slope [ft/ft]	0.325
Curve Number	81
Time of Concentration [minutes]	30.6
Lag Time [minutes]	18.4

Assume baseflow [cfs] (constant monthly estimation method) is 0. Execute the model, the pre-fire peak discharge using HEC-HMS is: see table C-8.

- ❑ Postfire Models

Table C-8—HEC-HMS Bull Fire #3 prefire peak discharge

Event	TR-55 pre-fire Q [cfs]
2-yr	148
5-yr	252
10-yr	353
25-yr	514
50-yr	653
100-yr	808

Modifier variables for USGS Regression Model

A_H (Bull Fire #3 high severity) = 0.008 mi^2

A_M (Bull Fire #3 moderate severity) = 1.306 mi^2

A_T (Bull Fire #3 total area) = 1.60 mi^2

The percent runoff increase for the first postfire year can be estimated from long-term streamflow records or previous studies. This is identified as a problematic variable. Methods to estimate this variable are ambiguous.

Understanding how to estimate this value without adding too much uncertainty is critical as the percent runoff ultimately influences the post-fire runoff estimates. The percent runoff increase is estimated as 147 percent (Bull Fire BAER Report).

Calculate the post-fire modifier (2.21). Adjust prefire Q_{pk} estimates from all models with the modifier to predict postfire floods.

Postfire peak flow using the USGS Linear Regression model, see table C-9.

Table C-9—USGS Linear Regression Bull Fire #3 postfire peak discharge

Event	Q [cfs]
2-yr	30
5-yr	97
10-yr	160
25-yr	292
50-yr	408
100-yr	582

Adjust prefire curve number for postfire
Using the prefire representative curve number for the entire watershed, adjust this curve number using the method by Higginson and Jarnecke (2007). Adjusted curve number 90.

Apply the postfire curve number to the Wildcat 5 and estimate post-fire peak flow, see table C-10.

Table C-10—Wildcat 5 Bull Fire #3 postfire peak discharge

Event	Q [cfs]
2-yr	289
5-yr	445
10-yr	585
25-yr	796
50-yr	970
100-yr	1160

Apply the curve number to the TR-55 model and estimate postfire peak flow, see table C-11.

Table C-11—TR-55 Bull Fire #3 postfire peak discharge

Event	Q [cfs]
2-yr	404
5-yr	626
10-yr	825
25-yr	1125
50-yr	1372
100-yr	1643

Apply the curve number to the HEC-HMS model and estimate postfire peak flow, see table C-12.

Table C-12—HEC-HMS Bull Fire #3 postfire peak discharge

Event	Q [cfs]
2-yr	235
5-yr	361
10-yr	476
25-yr	650
50-yr	795
100-yr	954

Appendix D—Monitoring Postfire Hydrology

This appendix is intended to provide specialists with additional knowledge of postfire hydrologic assessment and to provide guidance on tools that you can use to assist in postfire hydrologic monitoring and management. This includes an overview of methods to monitor in situ postfire hydrology, such as site selection and equipment installation (i.e., pressure transducers, tipping buckets, cross sections, etc.).

Channel Cross Section

Channel geometry affects streamflow velocity and discharge. Monitoring channel geometry through an in situ cross section can give estimates of postfire channel behavior and ultimately streamflow. A channel cross section is typically trapezoidal in larger streams or V- or U-shaped in smaller streams. It is used extensively in design and analysis. An ideal cross section should be away from bends and drops in the streambed. The endpoints of the cross section should be immobile (not easily washed away or moved by large flood events). The cross section also should be set up where there is a clear line of site for surveying equipment. Keeping safety in mind, implement the cross section as far away from hazards (i.e., unstable slopes, trees, poison oak, etc.) as possible.

Streamflow Measurements to Develop a Rating Curve

A rating curve is the relationship between the stage (depth or height) of the water and the streamflow. To construct a rating curve, normally the actual discharge is measured for various levels (stage) of flow. Use an equation like Manning's equation to estimate the discharge based on the geometry of the channel (Equation D-1).

$$Q = \frac{1.49AR^{2/3}\,S^{1/2}}{n} \qquad \text{Equation D-1}$$

A is the cross sectional area (ft^2), R is the hydraulic radius (cross-sectional area divided by the wetted perimeter [ft]), S is the slope (drop in elevation/length) and n is the Manning roughness coefficient (dimensionless).

Thus, Manning's flow is a function of (1) slope, (2) channel dimensions, and (3) channel roughness. Therefore, it requires field data for estimation of peak discharge. These data include determining the elevation and location of high-water marks along the stream, measurement of channel cross section and wetted perimeter by surveying, tape and compass, or GPS, and selection of a roughness coefficient for the section of stream or surface in question. By surveying a cross section and stream gauging often, we are able to add points to validate our rating curve.

Pressure Transducer Datalogger

Use various pressure transducers for obtaining streamflow height, including the Onset HOBO U20 Water Level Datalogger (max 13-foot depth), which can record water level, barometric pressure, and temperatures in shallow wells, streams, lakes, and freshwater wetlands for various time intervals. The HOBO is programmed prior to installation (name of the instrument, check battery, time interval, etc.) using the accompanying software, HOBOware Pro and coupler (device to connect to a computer). When you place it in the water the pressure transducer measures the total pressure above the sensor (fluid plus atmospheric pressure). You can translate the observed pressure data into a height (stage) by correcting for atmospheric pressure (independent sensor or regional data). Once you develop a rating curve (relationship

between stage and streamflow), you can use the continuous stage information to obtain streamflow at a high temporal resolution (5 minutes) throughout a 56-day period.

Installation

The HOBO is preprogrammed prior to installation. A start date and time is programmed, the battery level is checked, and the HOBO is given a name/description. A HOBO case is made from polyvinyl chloride (PVC) pipe with two ends that can be unscrewed. Make 1/2-inch-diameter holes in the body of the case to allow water to flow through, but blocks gravel. Suspend the HOBO in the PVC case with zip ties so that only the pressure of the water is consistently exerted on the HOBO. Place a fence post in the center of the selected cross section and secure the HOBO case and HOBO above the streambed to the fence post with zip ties. Note the height of the top of the fence post to the top of the HOBO and the height from the top of the fence post to the top of the water.

Data Retrieval and Reinstallation

The datalogger resolution—or the frequency that the HOBO records data—determines the memory capacity. For example, at the Bull Fire #3 in the Sequoia National Forest, we used the highest temporal resolution, which is data collection every 5 minutes. At this resolution, the data logger has enough storage for about 56 days of data. Use a coupler to connect the HOBO device to a laptop and download and reprogram the data. Reinstall the HOBO using the same steps as the installation protocol. Note the height of the top of the fence post to the top of the HOBO and the height from the top of the fence post to the top of the water; these measurements may have changed after the reinstallation.

Air Pressure

The HOBO measures all pressure exerted over it. While the HOBO is in the stream, it measures the water pressure as well as atmospheric pressure. We are only interested in the water pressure exerted. For accurate atmospheric pressure readings, we install a HOBO out of the streambed within close proximity. The location of the air-pressure HOBO should be out of the area of potential risk of being flooded. Often the air-pressure HOBO is above the stream channel or near an installed precipitation gauge. The air-pressure HOBO is programmed, installed, and the data is retrieved using the same protocol as the water HOBO. HOBOware can load the two time series of data (water pressure and air pressure) and calculate the water actual pressure exerted on the HOBO. This is the stage we used in our analyses.

Stream Gauging

Streamflow is an important variable in hydrology and water resources engineering; however it is difficult to make direct and continuous measurements of the rate of flow in a stream with low-cost equipment. However, it is relatively simple to obtain a continuous record of stage (height of the water), which is the primary field data gathered at most streamflow measurement stages are river stage. The measurement is necessary to establish an adequate correlation between stage and discharge. Since channel systems rarely have a regular shape for which you can compute discharge, accomplish the calibration by relating field measurement of discharge with simultaneous river stage. In most cases obtain the discharge at a section from point measurements of velocity.

A discharge measurement requires determination of sufficient point velocities to permit an accurate computation of discharge across the channel. Limit the number of velocity

determinations to those that you can make within a reasonable time, especially if stage is changing rapidly. The practical procedure involves dividing the stream into a number of imaginary vertical sections as shown where. No section should include more than about 10 percent of the total flow.

The velocity varies in the vertical approximately as a parabola from zero at the channel bottom to a maximum near the surface. On the basis of field and laboratory tests, the variation for most channels is such that the average of the velocities at 0.2 and 0.8 depth below the surface equals the mean velocity in the vertical. The velocity at 0.6 depth below the surface also closely approximates the mean velocity. As a general rule of thumb: If the stream is less than 1.5 feet deep, use the 0.6 depth reading. If the stream is greater than 1.5 feet deep, use the 0.8/0.2 depth readings to get an average. The following method is standard for stream gauging.

1. Select a stream cross section that is free of obstructions and the flow is relatively uniform (minimal turbulence). The discharge cross section should be the same or near the previously established channel cross section. Span the stream with a surveyor's tape between two fixed posts, stakes, or other object to which you can temporarily attach the tape. Ensure that the tape is taught, relatively level, and 1 to 3 feet above the stream surface. Attach the zero end of the tape to the stake on the left side of the stream viewing upstream.
2. Divide the channel into a reasonable number of sections (each no more than 10 percent of total flow).
3. Traverse the stream, while taking measurements in each section.
    a. Find the area of each section (depth x width).
    b. Take velocity readings at 0.6 depth (or 0.8 and 0.2 if is depth greater than 1.5 feet).
        i. Measure total depth of water (top-setting rod).
        ii. Raise the stream gauging meter to 0.6 * depth and measure the velocity.
4. Find total discharge for the stream (Q = V x A) by summing up the increments of discharge.

High Water Marks
You can estimate large flood events from physical evidence left behind, such as eroded soil, water lines on rocks, water-disturbed grass, etc. Note the high water mark location along an established cross section and use it to determine the discharge associated with this event.

Precipitation Instrumentation
Simple tipping buckets use a fulcrum set up to measure precipitation. A known volume fills the tipping bucket and the fulcrum tips and empties when full. Relatively inexpensive systems include the Rainwise Inc. or Onset rain gauge. It is a battery-powered rain gauge that is an 8-inch-diameter tipping bucket that meets the National Weather Service (NWS) specifications for statistical accuracy. The gauge is event-based and records each rainfall tip. Each tip of the bucket is equivalent to one hundredth of an inch. Each tip is a "count" and is transmitted to the internal recorder. The recording system is by Onset and requires a shuttle to program and download data.

Installation

Secure the tipping bucket to a fence post in an open area. The top of the tipping bucket is flush with the top of the fence post.

Data Retrieval and Reinstallation

You can retrieve the data using an Onset shuttle. The data collected is a date and time stamp of the event. From this data you can calculate the storm duration, rainfall intensity, etc.

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